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A Review of the limnology of and water quality standards for Lake Mead

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and
WATER QUALITY STANDARDS FOR
LAKE MEAD

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES, continued

LIST OF TABLES

Acknowledgements

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LIST OF TABLES, continued

I. EXECUTIVE SUMMARY

1. The waters of Las Vegas Bay, a heavily utilized recreational resource, receive discharges from a variety of municipal and industrial waste sources. The U.S. Environmental Protection Agency has determined, on the basis of numerous studies, that the present water quality violates state and federal standards and constitutes a public nuisance. Consultants have advised the Sewage and Wastewater Advisory Committee that rapid abatement of the alleged pollution conditions can be achieved by an advanced wastewater treatment (AWT) plant.

2. The major problems in Las Vegas Bay are an objectionable water color, excessive turbidity, noxious odors, and oxygen depletion in certain portions of the water column. Previous studies indicate that these problems are due to the effect of Las Vegas Wash on the Bay, and that the problems decrease as distance increases from the Las Vegas Wash inflow. The Wash provides a source of nutrients for high levels of algal production, which, in turn, are responsible directly for the pollution perceived by the public. Conditions in Boulder Basin, as opposed to those in Las Vegas Bay, have not reached an objectionable eutrophic level.

3. Most of the previous studies point to industrial and municipal wastewater discharges as the ultimate source of nutrients entering the Bay. One advisor argues that the nutrients arise from soil eroded into the Bay.

4. Adherents of the first position suggest that removal of nutrients from wastewater will abate the problems in Las Vegas Bay. Adherents of the second position suggest that control of soil erosion is the only step that can mitigate these pollution problems.

5. The following deficiencies in these previous studies prevent the formulation of a dependable strategy for decreasing the excessive algal production in Las Vegas Bay to acceptable levels:

(i.) There has been no detailed attempt to ascertain the fate of Las Vegas Wash inflow. The fact that the bulk of this inflow may leave the Bay in a well-defined current does not imply that partial mixing of the current with the Bay is not affecting algal production. The presence of enteric bacteria in the Bay suggests that partial mixing, in fact, is occurring.

(ii.) A systematic series of algal bioassays has not been undertaken to ascertain directly which nutrients limit algal production.

(iii.) Inputs of phosphorus other than via the Wash discharge have been neglected, particularly internal loading from the sediments to the water column.

(iv.) The effect of changing water level on dilution of nutrients in Las Vegas Bay has been neglected, despite the fact that the water volume in the Bay has increased about 75% between 1967 and 1976.

(v.) The standard of 0.5 mg l^{-1} phosphorus established by the EPA for Las Vegas Wash water does not rest on adequate evidence that these levels are necessary or sufficient to abate the problems in Las Vegas Bay, but rather upon the predicted performance of AWT.

(vi.) The studies have not been designed to predict changes in Las Vegas Bay following various alternative treatment strategies.

6. Ecological Research Associates initiated a field study of Las Vegas Bay and Boulder Basin (20-23 September 1976) to resolve certain discrepancies in previous studies and to provide supplemental information consistent with the short duration of the study.

7. Specific conductivity, temperature, pH, and oxygen profiles agreed with those collected by previous investigators. High conductivity values reflecting the presence of a well-defined current representing the Las Vegas Wash inflow were observed in Las Vegas Bay. However, this current was not detected at the mouth of the Bay in Boulder Basin. These results do not support the notion that the Wash inflow does not mix in the Bay, but the detailed investigation necessary to decide this issue could not be performed during the short time period of the study.

8. Virtually all dissolved phosphorus occurs in inorganic form and in very low concentrations, indicating that biologically-available phosphorus is cycling extremely rapidly and that the amount of analytically-detectable soluble phosphorus may not be particularly relevant for determining the potential algal production.

9. Algal productivity measurements in September were lower than those of previous investigators by more than 90% in some cases. The discrepancy

may represent differences in methodology or real decreases in algal production. Many hypotheses may be invoked to explain the results if the latter is the case, but insufficient evidence exists to distinguish between them. The results emphasize that important questions concerning the source and fate of inflowing nutrients remain to be answered, because previous studies cannot account unequivocally for this decrease in productivity. Severely eutrophic conditions were not observed in Las Vegas Bay during the course of this study.

10. Algal bioassays demonstrated that inner Las Vegas Bay algae are responsive to nitrogen because of the heavy phosphorus loading. Virgin Basin algae (and hence, presumably, Boulder Basin samples) are stimulated by addition of wastewater, nitrogen or phosphorus. Recalculated N:P ratios, based on previous studies, suggest that all Las Vegas Bay and Boulder Basin stations, except for the inner Bay, are most limited by phosphorus. The implication is that the middle and outer Bay and the Basin are sensitive to further loading of phosphorus. The uncertainty of decisions based upon nitrogen to phosphorus ratios is emphasized in this report.

11. Sediment analyses indicate that phosphorus is removed from the water by sedimentation. Proper standards for phosphorus concentrations in inflowing waters cannot be established without taking into account the role of phosphorus sedimentation in Las Vegas Bay.

12. The application of Vollenweider's relationship to Las Vegas Bay

suggests that, even if EPA standards of 0.5 mg l^{-1} phosphorus were met in Las Vegas Wash, the reduction in loading obtainable from present day AWT technology is not sufficient to produce the desired conditions in Las Vegas Bay. In any case, the Vollenweider relationship does not constitute an adequate basis on which to decide an abatement strategy for Lake Mead.

13. AWT treatment of Las Vegas Wash wastewater cannot guarantee the eradication of problems in Las Vegas Bay, both because the exact initial source of the nutrients is not established fully (i.e., wastewater or erosion) and because the effect of reducing phosphorus concentrations to 0.5 mg l^{-1} in the Wash cannot be predicted at present. The predictive relationship used by other consultants to justify AWT has not been applied correctly. The <u>correct</u> application of this relationship to the condition in Las Vegas Bay demonstrates, on the contrary, that AWT technology will not be sufficient. The enormous expense and deleterious side effects of AWT technology are not justified on the basis of existing data.

14. Numerous alternatives to AWT exist. Upgraded secondary wastewater treatment combined with biological stripping of both nitrogen and phosphorus in an expanded Las Vegas Wash marsh is the alternative that deserves special consideration. Control of soil erosion and partial discharge of treated wastes directly to Boulder Basin also should be considered in this scheme.

15. Any further study should be addressed to the following specific points:

(i.) The extent to which Las Vegas Wash inflow mixes with Las Vegas Bay water must be determined more precisely.

(ii.) The stimulating effect of eroded soil washed into the Bay on algal productivity must be determined.

(iii.) The level of algal growth that can be supported by water equivalent to that produced by various treatment strategies must be determined. A predictive model is recommended.

(iv.) The magnitude of the potential internal phosphorus loading from the sediment upon the eventual reduction of external loading should be investigated.

(v.) Downstream effects of alternative abatement strategies must be predicted.

II. INTRODUCTION

Lake Mead is an interstate impoundment of the Colorado River created by Hoover Dam and is located 15 miles east of Las Vegas, Nevada (Fig. 1). Las Vegas Wash is a tributary of the Colorado River that drains Las Vegas Valley and the Las Vegas metropolitan area, and then flows into Las Vegas Bay. It is an intermittent stream except for the lower 11 miles; a majority of the perennial streamflow in this reach consists of municipal (City of Las Vegas and Clark County Sanitation District) and industrial waste discharges. Las Vegas Bay is heavily utilized for water-based recreation, including fishing, boating, skiing and swimming. A small craft marina is located on the Bay near the mouth of Las Vegas Wash. Lake Mead also is used as a source of municipal water supply, with the intake located at Saddle Island near Boulder Beach.

Concern with the water quality of Boulder Basin in general and of Las Vegas Bay in particular resulted in a variety of technical investigations from 1966 to the present (reviewed in Section III of this report). These studies have suggested that direct and indirect discharge of wastes to Las Vegas Wash are polluting Lake Mead and the Lower Colorado River. The U.S. Environmental Protection Agency (1971) concluded that water quality conditions in Las Vegas Bay are in violation of Nevada standards requiring that the waters be "free from materials attributable to domestic or industrial waste or other controllable sources...in amounts sufficient

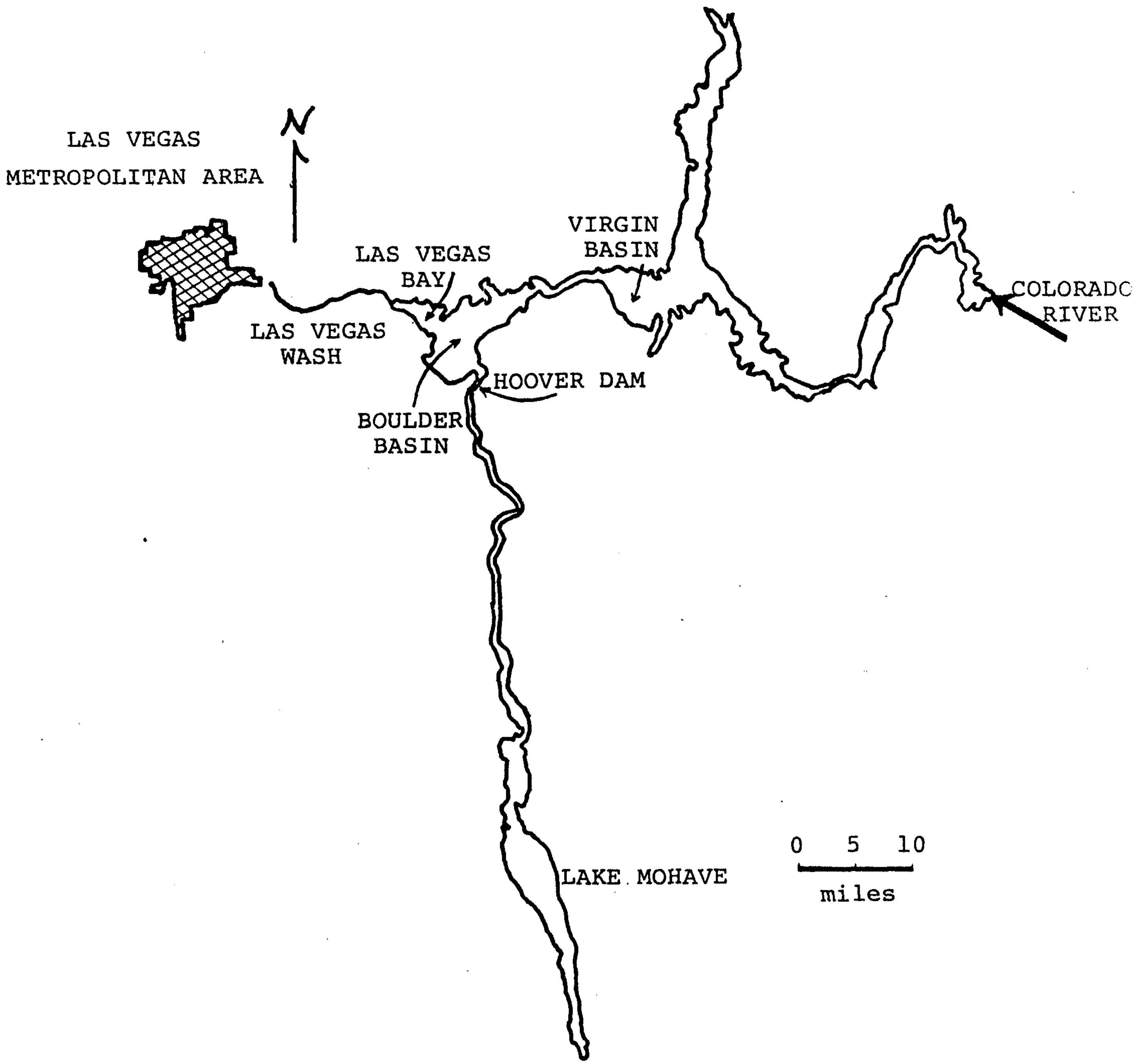

Figure 1. Regional map showing Lake Mead in relation to the Las Vegas metropolitan area and the lower Colorado River system.

to change the existing color, turbidity, or other conditions in the receiving stream to such a degree as to create a public nuisance, or in amounts sufficient to interfere with any beneficial use of the water." Furthermore, this pollution violates Federal-State water quality standards applicable to Lake Mead and the Colorado River (EPA 1971). Environmental quality and water development has become an increasingly important concern of planners, and public involvement in the planning process has greatly increased in recent years (Goldman, McEvoy, and Richerson 1973.)

As a result of these developments, the Clark County Sanitation District, the City of Las Vegas and other representatives of Las Vegas Valley municipal and industrial waste sources have met with personnel of the Environmental Protection Agency to determine means by which the pollution of Lake Mead via Las Vegas Wash can be stemmed and to evaluate the validity of current numerical water quality standards for the area. Dr. James E. Deacon, who has directed Lake Mead water quality studies since 1972, recently advised the Sewage and Wastewater Advisory Committee that a marked and relatively rapid abatement of pollution conditions in Las Vegas Bay and Boulder Basin could be achieved through sewage treatment (and ultimately phosphorus reduction) by an advanced wastewater treatment (AWT) plant. For an additional independent opinion, the Clark County Sanitation District has requested Ecological Research Associates both to assess the adequacy of AWT in meeting the pertinent regulation and to critically examine the validity of the numerical standards themselves.

To accomplish these goals, the water quality standards for and available relevant literature on Lake Mead, and specifically Las Vegas Wash and

Las Vegas Bay, were reviewed and deficiencies were noted (Section III). An overall summary of the conclusions that can be substantiated by this previous work (Section IV), as well as conclusions arrived at in a limited field study by Ecological Research Associates (Section V), follow. A general discussion and an analysis of alternative abatement strategies are then presented (Section VI), followed by conclusions (Section VII), and a list of recommendations (Section VIII).

III. CRITICAL REVIEW OF EXISTING LITERATURE

1. "Water Quality Study of Lake Mead." 1967. U.S. Dept. of the Interior, Bureau of Reclamation, Chemical Engineering Branch, Report No. ChE-70. 81 pp.

This is a report of Lake Mead water quality data obtained from 1964 to 1966. It is a general limnological survey of the lake's temperature, dissolved oxygen, carbon dioxide, conductivity, light transparency, algal growth nutrients, and mineral quality. This study noted the warm monomictic temperature cycle and the metalimnetic dissolved oxygen minimum during stratification. Also, the inflow from Las Vegas Wash was assigned particular importance as it was identified as a major source of wastes which contribute to the deterioration of water quality in Lake Mead; future study in this locale was recommended.

This report has historical interest since it was the first to document the potential pollutional problems from Las Vegas Wash effluents. It is also valuable in providing background data against which present and future changes can be weighed.

2. "Report on Pollution in Las Vegas Wash and Las Vegas Bay." 1967. U.S. Dept. of the Interior, Federal Water Pollution Control Administration. 19 pp.

This was the first study designed to ascertain the effects of waste water discharges from Las Vegas Wash on Lake Mead. Although data was collected during a limited sampling period (late May 1966), certain results are of interest. It was concluded, for example, that there was no evidence that bacterial pollution was causing any damage to water quality in Las Vegas Bay. However, the report noted that a distinct green color was imparted to areas of Las Vegas Bay when algal cell density exceeded approximately 2000 ml^{-1} (counts reached as high as 23,800 ml^{-1} at the mouth of Las Vegas Wash, then declined rapidly to 9000 ml^{-1} three miles from the Wash). The FWPCA then concluded that to maintain cell density at less than 2000 ml^{-1}, it is necessary that total phosphorus in the Bay not exceed 0.005 mg l^{-1} at any point. They also stated that phosphorus was limiting algal growth whereas nitrogen was not. These conclusions should have been offered as tentative since they were based on only a few weeks of data and they have since been seriously challenged; nevertheless, the study is important in its documentation of algal growth which produced objectionable aesthetic conditions which, it was predicted, could eventually destroy the recreational use of the area.

3. "The Effect of Las Vegas Wash Effluent upon the Water Quality in Lake Mead." by D.A. Hoffman, P.R. Tramutt, and F.C. Heller. 1971. U.S. Department of the Interior, Bureau of Reclamation, REC-ERC-71-11. 22 pp.

Results from the two previous studies prompted this more detailed investigation of Las Vegas Wash effluent. Stations in the Wash, Las Vegas Bay and Boulder Basin were sampled on a seasonal basis in 1968. The following parameters were measured: DO (dissolved oxygen), CO_2, Secchi depths, alkalinity, pH, conductivity, orthophosphate, total P, NO_3-N, NH_3-N, organic N, chlorophyll, and numerous elements. The data demonstrated an increase in all parameters, except carbon dioxide, bicarbonate, orthophosphate and nitrate, as water passed through Las Vegas Wash. Uptake of phosphorus by aquatic plants in the Wash was suggested as the likely cause of its decline. Also, it was concluded that the salt load from Las Vegas Wash is an important contributor to the salinity of Lake Mead.

The final conclusion was that "discharge from Las Vegas Wash is contributing to the eutrophication of Lake Mead by adding nutrients which support an algae bloom in the Las Vegas Bay reach of Boulder Basin." The thoroughness of the sampling design and the detailed sections on methods of analysis impart a high level of credibility to these data.

4. "Effects of Water Management on Quality of Ground and Surface Recharge in the Las Vegas Valley" by R.F. Kaufman, A.E. Peckham, and J.M. Sanders. 1971. University of Nevada, Center for Water Resources Research, EPA Project No. 13030EOB. 74 pp.

This document provides a thorough treatment of the historical developments that prompted the reported groundwater studies and of the progress to date. Important points include the documentation of: (i) increasing salinity in shallow valley-fill deposits which ultimately discharge into Las Vegas Wash; (ii) subsurface migration of industrial wastes from plant and tailings pond areas directly to Las Vegas Wash; and, (iii) the infiltration of sewage effluents into the Wash sediments, increasing TDS (total dissolved solids) 2-fold and nitrate 100-fold. The authors account for the progressive decrease and then increase of total N as it passes along the Wash. Also included is a good summary of TDS, N, P, trace metals, and various ions emanating from each of the sewage treatment plants, power stations and industrial facilities along the Wash.

5. "Report on Pollution Affecting Las Vegas Wash, Lake Mead and the Lower Colorado River" 1971. U.S. Environmental Protection Agency, Office of Enforcement, Division of Field Investigations, Denver. 52 pp.

This is the best single summary of the problem at hand. The report summarizes the technical information documenting the interstate pollution, notes where regulations are being (or will be) violated, and recommends remedial abatement action. Water quality and discharge volumes of effluent from each major contributor along Las Vegas Wash are summarized. Water quality standards for Nevada, California and Arizona are included in an appendix.

Conclusions are that water quality conditions in Las Vegas Bay are in violation of Nevada standards, waste treatment technology is available that will reduce nitrogen and phosphorus to levels necessary to meet 1973 standards for Las Vegas Wash, but available technology could not produce an effluent that would meet more stringent 1980 requirements. Consequently, the EPA recommended in this report that municipal waste waters be collected and treated so as to achieve a maximum practicable removal of phosphorus and nitrogen, consistent with available technology. Ponding, elimination of once-through cooling and pumping of contaminated ground water also were recommended.

6. "A Mathematical Model of Primary Productivity and Limnological Patterns in Lake Mead" by L. G. Everett. 1972. Univ. Arizona, Technical Reports on Hydrology and Water Resources, Report No. 12. 151 pp.

This is a report of a doctoral dissertation describing temporal and spatial changes in biological properties of Lake Mead. It contains a useful summary of related investigations since completion of Hoover Dam in 1936. The report also discusses in a general sense the major components of an aquatic system and, accordingly, is of value to the nonscientific reader.

The experimental design was based on eight stations throughout the lake which were sampled from 1970-1972. Parameters studied include temperature, DO, pH, chlorophyll, light transparence, solar radiation, phytoplankton and zooplankton counts, ^{14}C phytoplankton productivity, conductivity, and various macro- and micronutrients. Finally, a regression model designed to relate primary productivity to certain physical and chemical parameters was offered as a first approximation for prediction and management utility.

Although this report has value as part of the continuing accumulation of data on Lake Mead, it suffers from a deficiency of purpose and frequent oversimplification. Little new information was presented (with the exception of ^{14}C primary productivity measurements), and that which was new is challengeable because descriptions of analytical techniques are incomplete and not referenced. For example, measurement of orthophosphate concentration can be widely variable depending on the analytical method, time of sample storage, preservative added, and so forth; these are not reported. The regression model also suffers from its disregard of interaction among the independent variables; thus, it is difficult to make predictions outside the range for which the model was constructed. Use within the range is also limited because it is easier to measure phytoplankton productivity than all the other parameters needed to predict it. Finally, the conclusions are weak and in many cases not supported by the data.

7. "Interrelationships between Chemical, Physical and Biological Conditions of the Waters of Las Vegas Bay of Lake Mead" by J.E. Deacon and R.W. Tew. 1973. University of Nevada, Las Vegas. 186 pp.

This is a report of Dr. Deacon's initial study of the effects of Las Vegas Wash on Las Vegas Bay. It primarily concentrated on identification and counting of algae, but also examined other physical, chemical and biological parameters. One notable aspect of this report is the thorough treatment and documentation of the experimental design, sampling techniques and analysis, and statistical evaluation. More importantly, this was the first long-term study which addressed itself to the entire Las Vegas Bay ecosystem and which attempted to explain, rather than merely describe, some of the lake's unusual phenomena.

Dissolved oxygen data suggested to the authors that sediment surfaces have remained oxidized, thus internal phosphorus loading in the system may be minimal. This observation may explain the oligotrophic condition of the lake during the spring and demonstrates the importance of nutrient loading from Las Vegas Wash. Based on conductivity values, the report suggested that in the summer the Las Vegas Wash is a distinct current which releases nutrients to the epilimnion at the inner portion of Las Vegas Bay. The current is progressively mixed throughout the water column as it passes through the Bay.

Although the nutrient enrichment study reported was rather crude and limited in areal coverage, it did demonstrate that at the inshore station algal growth is most severely limited by nitrate, and less so by minor elements and phosphate. It was suggested that a high phosphate input from Las Vegas Wash results in initial nitrogen limitation, but that phosphate may become limiting further into the Bay as nitrogen is progressively assimilated. Further support for this hypothesis is the observed high phosphate concentrations at North Shore Road and the rapid dilution (and lowered phosphate concentrations) as Las Vegas Wash enters the Bay.

Also of interest is the study of shad distribution patterns. From these data the authors suggested that shad respiration along with bacterial decomposition of shad excreta and other detritus was the major cause of the observed metalimnetic oxygen minimum.

8. "Lake Mead Monitoring Program. Final Report." by J.E. Deacon. 1975. Department of Biological Sciences, University of Nevada, Las Vegas. 207 pp.

This report is essentially a continuation of the studies initiated in 1972 (see above). Additional data on phytoplankton populations and discussion of distribution and abundance patterns are included. The metalimnetic oxygen minimum was examined further and zooplankton respiration was hypothesized as the major cause. Study of bacteria in Lake Mead and Las Vegas Wash was intensified, but the investigators were not able to make any definite conclusions regarding water movements. Vollenweider's eutrophication index was used to calculate a "permissible" phosphorus loading of 800 lbs day^{-1} from Las Vegas Wash; however, the data applied in the calculations were not included (e.g., were area and mean depth determined from high or mean lake level?), it is not stated whether retention time (a necessary parameter in Vollenweider's revised formula) was considered, and even the authors noted that this is a tentative value because of certain broad assumptions.

Pigments also were analyzed, but again the authors identify their conclusions as tentative. Remote sensing techniques were attempted, but without success. Tests of algal growth potential (AGP) yielded generally expected results, and the authors pointed out that AGP standards appear to be of limited value, especially when compared to more efficient and theoretically more valid methods such as ^{14}C primary productivity measurements. The summary section reported that ^{14}C measurements were made; however, no description of methodology or data summaries are included.

9. "Lake Mead Monitoring Program, Final Report." by J.E. Deacon. 1976. Dept. of Biological Sciences, University of Nevada, Las Vegas. 182 pp.

Much of the data from this continuing study will prove to be important in providing a historical perspective against which future changes in Lake Mead can be weighed. It also further corroborates results from previous studies which have shown Las Vegas Wash to be enriched in growth-stimulating nutrients. Beyond this, little information relevant to assessment of sewage treatment designs and other abatement alternatives is offered.

^{14}C primary productivity data were first reported, and as expected, values increased from the mouth of Las Vegas Wash into Las Vegas Bay. The highest productivity occurred in August and September. Unexpected is the absolute magnitude of productivity, which exceeds Everett's (1972) values by a factor of from 3 to 5. Since other algal growth parameters have not indicated such an increase during this 4-5 year period, the discrepancy is likely attributable to methodological errors which severely limit the usefulness of both sets of data; however, a detailed analysis of such potential errors is not possible because of Deacon's failure to adequately describe his methodology.

Also of concern is the author's conclusion that 350 kg day^{-1} of phosphorus from Las Vegas Wash would result in a permissible loading rate to Boulder Basin. The data and narrative explanation provided are not detailed sufficiently to permit evaluation without complete recalculation.

10. "Statement prepared for Clark County Commission public hearing on pollution of Lake Mead." by V. Bostick. 1976. Desert Research Institute, University of Nevada. 11 pp.

This report attributes most of the nutrient loading of Las Vegas Bay to soil erosion in the watershed, and emphasizes that only a small portion of Boulder Basin (inner Las Vegas Bay) can be considered truly eutrophic. Secchi depth and phosphorus concentrations are used as evidence that the water cannot be considered eutrophic, but the author erroneously assumes that only soluble P need be taken into account, contrary to well-established evidence of the high turnover rates of soluble

P (Hayes et al. 1952, Hayes and Phillips 1958, Pomeroy 1960, Phillips 1963, Rigler 1964) and storage of inorganic P by algae. The author suggests that Las Vegas Wash wastewater does not mix with water of the inner bay, but flows along the bottom in a density current without affecting fertility of Las Vegas Bay. The point is made that, even with AWT technology, the N:P ratio in the inner Bay still will be too low to render phosphorus the limiting element to algal production. Finally, it is argued that control of soil erosion is the only effective method for reducing the fertility of inner Las Vegas Bay.

This statement is the first to point out soil erosion as a major cause of eutrophication in Las Vegas Bay and to emphasize that an objectionable trophic state exists only in the vicinity of the Wash discharge. It does not demonstrate conclusively that the wastewater does not mix with Las Vegas Bay to an extent that promotes undesirable algal production levels. The two pieces of evidence cited, the lower proportion of soluble P and the lower N:P ratios in Las Vegas Bay with respect to wastewater, are discussed without reference to the chemical and biological activity that may account for these results. The "supplemental statement" noting a tremendous increase in total P for the inner Bay during the last five years ignores the possibility of internal loading from previous wastewater P that has been absorbed or adsorbed and sedimented (Stumm and Leckie 1971). Sediments may actually remove phosphorus from waters already high in phosphorus by adsorption (Carritt and Goodgal 1954, MacPherson et al. 1958, Jitts 1959, Harter 1968, Williams et al. 1970, Latterell et al. 1971, Shukla et al. 1971). Too little attention is paid to the possibility that the phosphorus from eroded soil may be unavailable for algal growth (Sagher and Harris 1972, Golterman 1973).

IV. CONCLUSIONS FROM PREVIOUS STUDIES

The major problems in Las Vegas Bay are an objectionable water color, excessive turbidity, and noxious odors, leading to an impairment of recreational activity such as swimming, skiing, and fishing, and a possible deterioration of Las Vegas potable water supplies. These problems are perceived by the public, and the Environmental Protection Agency has declared that such conditions create a public nuisance or interfere with beneficial uses of the lake.

The above reports have demonstrated that these problems are due primarily, if not entirely, to the inflow of Las Vegas Wash, which carries high concentrations of algal nutrients (particularly phosphates and nitrates) into Las Vegas Bay. These nutrients stimulate the production of high concentrations of algae whose presence is directly responsible for the color, turbidity, and at least some of the odor problems. The large algal populations are responsible, in turn, for a precipitous decrease in oxygen levels in the metalimnion, due to a combination of bacterial, fish, and zooplankton respiration, all of which depend ultimately upon the algae for their continuation. The reports also demonstrate a declining effect of the Las Vegas Wash as distance increases from the point of inflow.

An additional conclusion from the above studies is that, if control is to be achieved through removal of a nutrient from the Las Vegas Wash discharge, then phosphates should be reduced. This is based on the almost complete point source of phosphate (as opposed to the more diverse sources of nitrogen, such as by groundwater inflow and biological fixation) and the relative effectiveness of AWT in phosphorus reduction.

Although these reports have been useful in documenting the problems, they have not addressed the more immediate concerns of exactly how these problems can be abated and whether current applicable water quality standards are appropriate for producing desirable conditions in the lake. Further, the reports are not unanimous in pointing to the ultimate source of the problem. V. Bostick, in a statement to the Clark County Commission, argued that soil erosion is the major factor. J. Deacon concluded from his lengthy studies that municipal and industrial effluent was the culprit. There is a corresponding lack of agreement on the solution, Bostick favoring erosion control and Deacon supporting an AWT plant. As noted above, reduction of phosphates is the most appropriate starting point, but the question remains as to what strategy for nutrient removal should be chosen. The following deficiencies in the above collection of reports leave this problem with no simple or totally satisfactory solution at present:

(i.) There has been no thorough attempt to ascertain the fate of the Las Vegas Wash inflow. In their 1967 report, the Bureau of Reclamation recommended that these current patterns be examined by tracer studies, drogues, floats, and current meters. Such information as the degree of mixing of Las Vegas Wash water and its retention time in Las Vegas Bay is necessary for an accurate prediction of the effects of sewage treatment plant effluents on Las Vegas Bay. Similarly, the flow patterns and extent of circulation of the Las Vegas Wash-Las Vegas Bay inflow within Boulder Basin is needed for a reasonably accurate assessment of sewage treatment plant effluents on Boulder Basin and the lower Colorado. The dye studies of John Baker (Deacon 1976) are suggestive but not conclusive as to the annual regime of nutrient transport through Las Vegas Bay. In addition, the statement by V. Bostick that wastewater does not affect Bay water is inconsistent with the high levels of enteric bacteria in Las Vegas Bay. These bacteria function as tracers for the fate of the wastewater discharge.

(ii.) These studies also have failed to take a direct approach to the analysis of limiting nutrients; i.e., by means of a thorough, systematic algal bioassay. Indirect measures such as N:P ratios (which are confusing enough because of different analytical techniques, different analytical fractions of the nutrients used for calculation of ratios, and the occurrence of nitrogen-fixing algae) are inconclusive.

(iii.) Previous studies neglected to consider inputs of phosphorus other than stream inflow. Internal loading (from the sediments to the water column) has been discarded as insignificant on rather indirect evidence. Other potentially important inputs, such as precipitation, dry fallout, groundwater inflow, and dissolution of phosphatic minerals, were not considered.

(iv.) Existing studies have failed to consider the effect of changing water level (and hence volume) on the algal growth parameters in Lake Mead. From 1967 to 1973, the water level rose from 1130 to 1185 feet elevation, declined to 1170 feet by mid-1974, then rose to about 1180 feet by mid-1976. Although such changes in lake level may be of minor significance in Boulder Basin, they could be very significant as a factor affecting dilution of nutrients in the shallow portions of Las Vegas Bay, where the algal problems are reported to be most acute.

(v.) The goal of the concerned agencies is to reduce the Las Vegas Wash nutrient load, specifically phosphorus, to a degree that will produce "acceptable" levels of algal growth. The EPA has established 0.5 mg l^{-1} phosphorus as an acceptable concentration in the Wash, but there is no available empirical data to justify the validity of this value. The value apparently was arrived at by estimating the efficacy of current AWT technology, but no documentation exists that this standard will result in an acceptable level of algal growth. Although it is possible that the 0.5 mg l^{-1} standard is appropriate, it obviously is an unwise move to invest the amount of money required for AWT if there is a reasonable likelihood that the problems may not be abated sufficiently and that alternative, less expensive, strategies may be equally or more effective.

The only evidence which supports the adequacy of a 0.5 mg l^{-1} standard is Dr. Deacon's application of Vollenweider's semi-empirical method of estimating "permissible" nutrient loading rates (e.g., Vollenweider and Dillon 1974). Vollenweider showed that, for a lake of mean depth $\bar{Z}$ and water turnover time τ_w, a nutrient loading rate L_p (the "permissible" loading) can be calculated, below which a lake would remain oligotrophic. A second loading rate L_d (the "dangerous" loading) can be calculated, above which a lake becomes eutrophic. Between L_p and L_d, the lake is in a mesotrophic state. The technique is an empirical one in that L_p and L_d are selected through experience with a large number of lakes, mostly temperate North American and European lakes. One tacitly assumes, in applying this technique, that the inflow mixes rapidly throughout the entire lake without remaining in a confined area for too long. Vollenweider later refined the method to include the effects of nutrient losses to the lake bottom where they become inaccessible for phytoplankton growth. He replaced L_p and L_d by L_p (1-R) and L_d (1-R), respectively, where R is the fraction of the inflowing nutrients retained by the sediments. As R becomes greater than zero, a proportionately larger loading rate is allowed to produce the same effect on a lake.

Dr. Deacon has calculated, on this basis, that Boulder Basin is capable of sustaining a 2000 lbs day^{-1} phosphorus inflow. Since approximately 1200 lbs day^{-1} enter from Virgin Basin, he concludes that the Las Vegas Wash loading must be a maximum of 800 lbs day^{-1}, or 400 lbs day^{-1} to allow a reasonable safety margin. Because present Las Vegas Wash loading is about 1800 lbs day^{-1}, a reduction of present phosphorus levels in the Wash (5 mg l^{-1}, approximately) to 0.5 mg l^{-1} would result in a loading of 180 lbs day^{-1}, well within the permissible loading rate. In his testimony to the Nevada State Commission on Environmental Protection on 12 June 1973, Dr. Jack E. McKee, a noted scientist in the field of water quality standards, relied extensively on Deacon's calculation of permissible phosphorus loading in his recommendation that total P not exceed 0.5 mg l^{-1} in discharges to Las Vegas Wash.

There are two problems with the above analysis. First, Dr. Deacon gives no explicit calculations, so it is difficult to know whether or not he assumed that $R = 0$. If he did assume $R = 0$, then the inclusion of a non-zero R would raise substantially the permissible loading rate to Boulder Basin. Second, and more important, it is irrelevant to consider the L_p for Boulder Basin when the major problem is in Las Vegas Bay. In order to establish standards for Las Vegas Wash, it must be recalled that the Wash inflow does not mix instantaneously with Boulder Basin, but is retained for varying periods of time in the Bay. Therefore, the calculation can be applied meaningfully only to Las Vegas Bay where the problems are most severe.

(vi.) Aside from the above specific deficiencies, the major overall problem with the studies to date is that they have been oriented merely toward describing the Lake Mead system, which is necessary but certainly not sufficient for the task at hand; i.e., predicting changes in the system in order to permit intelligent decisions on water quality standards and waste water treatment strategies to be made.

V. PRESENT STUDY

ERA initiated a limited field study of Las Vegas Bay and Boulder Basin from 20-23 September 1976 in order to resolve discrepancies noted in previous investigations. The objectives of our study were:

(i.) to determine vertical and horizontal patterns of algal productivity, nutrient concentrations, and physical-chemical factors in Las Vegas Bay and Boulder Basin as influenced by nutrient loading of Las Vegas Wash;

(ii.) to verify methodology used in previous investigations, particularly in regard to determining levels of orthophosphate and algal productivity in Las Vegas Bay and Boulder Basin;

(iii.) to experimentally evaluate by systematic enrichment bioassay procedures nutrient limitation of algal productivity in Las Vegas Bay and an area unaffected by wastewater inflow;

(iv.) to observe first hand the quality of water in Las Vegas Wash, Las Vegas Bay, and Boulder Basin.

It must be emphasized from the outset that, because of time considerations, the present field study was designed to provide only supplementary limnological information. Although we did not expect the results of this study to provide a complete solution to the many problems already identified, it proved essential to verify previous data and to provide a better basis for recommendations and for refocusing future studies of Lake Mead toward the specific problem of pollution abatement.

A. Methods

1. Physical-Chemical Measurements

Water column profiles of temperature, pH, specific conductivity, and dissolved oxygen were determined at 11 stations in Las Vegas Bay and Boulder Basin (Fig. 2) by *in situ* measurement with a Hydrolab water quality monitoring unit. Secchi disc transparency was determined, and vertical light profiles were obtained with a Li-Cor Quantum meter.

At each sampling station and depth, 500 ml of lake water was collected, frozen, and returned to the laboratory for analysis of NO_3-N, PO_4-P, total soluble P, and total P. Nitrate-N was determined by the hydrazine reduction technique of Mullin and Riley (1965). All phosphorus analyses were by the molybdenum blue method of Murphy and Riley (1962). Total P was determined after acid hydrolysis of unfiltered samples, total soluble P after acid hydrolysis of samples filtered through GFC filters, and PO_4-P from unhydrolyzed filtered samples.

2. Primary Productivity Measurements

Although numerous parameters have been used to measure algal growth, primary productivity measured with the sensitive ^{14}C technique is probably the best single indicator of a lake's trophic status in most systems, including Lake Mead. This technique involves inoculation of lake water samples with radioactive carbon (in the form of $H^{14}CO_3$) and the incubation of these samples *in situ* for a known period of time. During this incubation period, ^{14}C is photosynthetically assimilated by the algae. Algal cells (containing ^{14}C) are then filtered

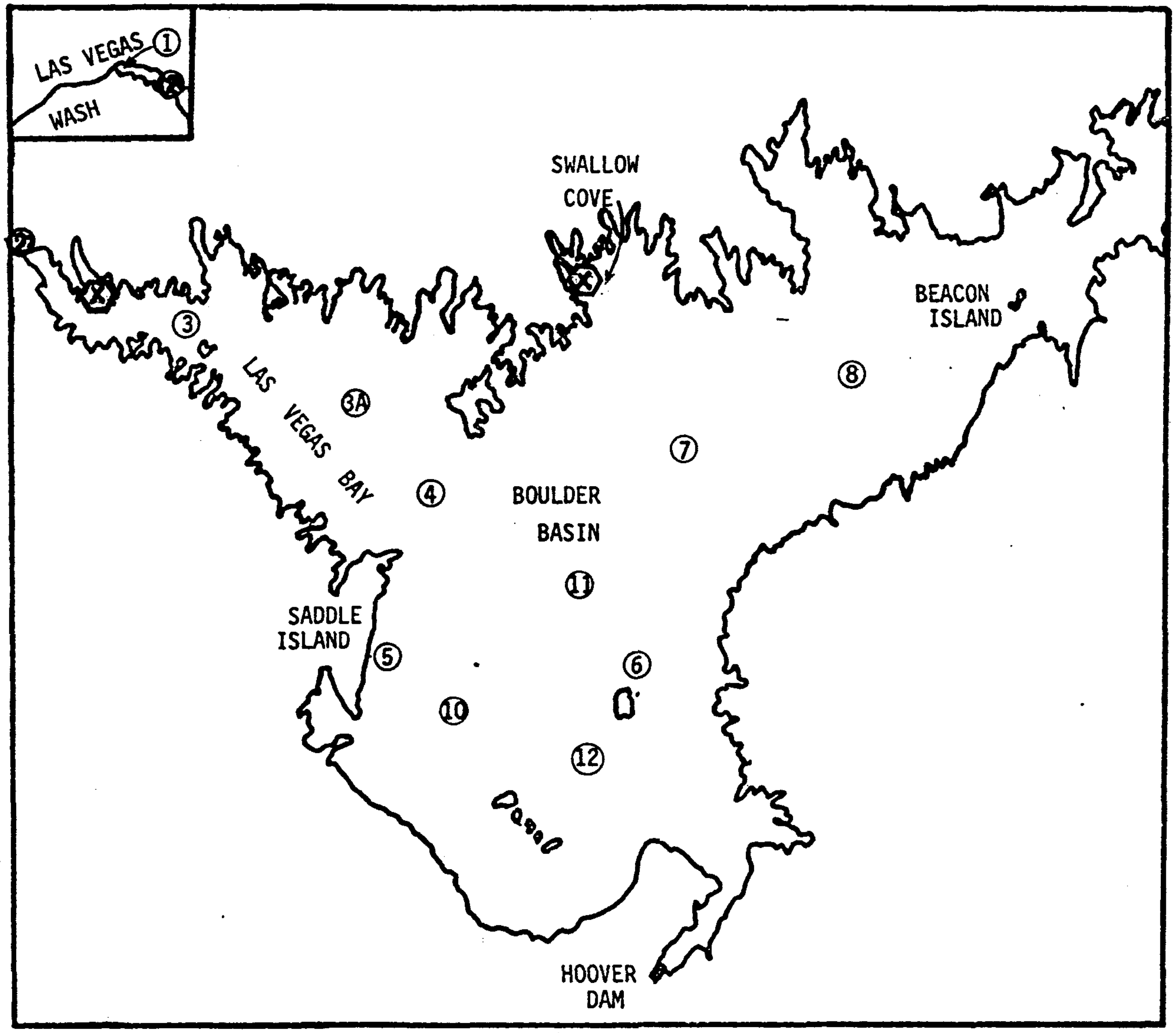

Figure 2. Map of the Las Vegas Bay and Boulder Basin of Lake Mead showing sampling stations for algal productivity, water chemistry, and physical-chemical measurements. Ekman dredge samples were taken at stations 1 and 2. ⟨X⟩ shows where the two core samples were taken. ERA study.

from the samples and the radioactivity of the filters is determined. In conjunction with data on solar radiation (both during the period of incubation and throughout the entire day) and the total amount of carbon available for assimilation, the activity of the filters is converted to hourly and daily rates of carbon uptake per volume of lake water. Carbon uptake rates are equivalent to algal productivity, which, in turn, is an indicator of the trophic status of the lake.

a. Vertical Profiles

Las Vegas Bay (Station 4) was sampled on 20 September 1976 at 0, 1, 2, 3, 4, 5, 7, 10, 15, and 20m with a 4-liter PVC Van Dorn bottle. This station was selected because it represented an area of the lake where excessive algal growth and other objectionable condition have been noted and also to provide continuity with Deacon's data. Based on previous studies, we selected the appropriate depths to provide a reasonably complete coverage of the important points of algal productivity, including maxima, minima and areas of rapid change. Station 12 in Boulder Basin (U.S. Bureau of Reclamation raft, Fig. 2),where algal cell densities have been noted as acceptable, was also sampled at these depths on September 20.

The methods used for algal productivity measurements are those of Steeman-Nielsen (1952) as modified by Goldman (1963). At all stations at each depth, three 125 ml glass-stoppered Pyrex bottles (2 light, 1 dark) were filled under a dark shield, stoppered, and kept in a dark box until all samples were collected. Each bottle was then inoculated with 0.5 ml of $NaH^{14}CO_3$ solution (5.2 $\mu Ci\ ml^{-1}$ activity) and suspended at the depth from which the sample was taken at the U.S.B.R. raft for ca. 4 hours during midday. After the incubation period, bottles were returned to the laboratory in a dark box, and 25 ml from each bottle were filtered through 0.45 μ Millipore filters at low (100 mm Hg) vacuum pressure. Filters were rinsed with 5 ml 0.1N HCl to redissolve precipitated ^{14}C-carbonates, rinsed with distilled water, and dried. The radioactivity of each filter was determined on an ultra-thin window gas-flow Geiger-Muller counter, calibrated with National Bureau of Standards $BaCO_3$ samples of known activity in gas phase (Goldman 1963).

In conjunction with algal productivity sampling, an additional water sample was collected from each sampling depth in a 125 ml glass-stoppered Pyrex bottle for total alkalinity determination. The pH of each sample was determined with a laboratory pH meter, temperature with a hand-held thermometer, and total alkalinity by titration of 100 ml of sample with 0.02 N HCl to pH 4.5 (Amer. Pub. Health Assn. 1971). Total ^{12}C available for algal uptake was then calculated using the conversion table of Saunders, Trama, and Bachman (1962). A Belfort pyrheliometer placed in an unshaded location on a small island in Boulder Basin recorded solar radiation during both days of our field study (20 and 21 September). The calculation of algal productivity is detailed by Goldman (1963) and Vollenweider (1969).

b. Synoptic Measurements of Algal Productivity in Las Vegas Bay and Boulder Basin

In order to evaluate the spatial variation of algal productivity, 11 stations throughout Las Vegas Bay and Boulder Basin (Fig. 2) were sampled at 2 and 5 m on Sept. 21. All field and laboratory methods were as described above.

3. Nutrient Enrichment Bioassays

An algal bioassay is the single best method for determining which nutrient factors limit algal productivity in aquatic systems. By inoculating lake water samples with known concentrations and combinations of nutrients, and measuring the growth response with the ^{14}C method, it is possible to determine which nutrient or nutrient combination is most likely to stimulate algal growth if added to the system or to reduce algal growth if removed from the system. We tested the effect of NO_3-N and PO_4-P additions to lake water samples from two areas of Lake Mead, one affected by wastewater inflow (inner Las Vegas Bay) and the other unaffected by wastewater inflow (Virgin Basin). Additionally, small quantities of wastewater effluent were added to Virgin Basin samples to directly assess the effect of nutrient enrichment in this form.

On Sept. 20, 12 liters of water were collected from 2m at the mouth of Las Vegas Wash (a site with relatively high algal productivity) and Virgin Basin (relatively low algal productivity). Sample water was immediately filtered through coarse mesh (150 μ) plankton netting to remove zooplankton and then returned to the lab in large polyethylene jugs. After various concentrations of N, P, and filtered wastewater were added to 500 ml Erlenmeyer culture flasks, a measured volume of ^{14}C-labeled sample water was added to each flask (Table 1). Flasks were incubated under continuous fluorescent illumination (26.1 micro-

TABLE 1

Wastewater additions to Virgin Basin water bioassay experiment. Additions are presented in terms of volumes of filtered wastewater actually added and the corresponding increase in NO_3-N and PO_4-P concentrations. 20 September 1976, ERA data.

STARTING MEDIA	TREATMENT		
Virgin Basin Water	+ HA Filtered Wastewater from Las Vegas Wash		
volume (ml)	volume added (ml)	equivalent nutrient increase($\mu g\ l^{-1}$) NO_3-N	PO_4-P
400	0.001	0.001	0.005
"	0.01	0.007	0.047
"	0.1	0.070	0.467
"	1	0.701	4.656
"	10	6.854	45.536
"	20	13.381	88.905

einsteins cm^{-2}) at a temperature of 26 $\pm$ 1°C. Over a 60-hour incubation period, 5 subsamples were taken from each flask, filtered, and the radioactivity determined by the methods described above. In order to detect possible changes in algal species composition, subsamples were taken from the initial lake water sample at the beginning of the bioassay experiments and from each culture flask at the termination. These samples were preserved with Lugol's solution for phytoplankton enumeration.

4. Phytoplankton Identification and Enumeration

In conjunction with algal productivity sampling on Sept. 20 and 21, samples were taken at each station for identification and enumeration of phytoplankton. Samples were preserved with Lugol's solution, refrigerated, and phytoplankton counted using the Ütermohl (1958) settling chamber technique.

5. Sediment Analysis

Previous investigators have concluded that P release from the sediments is not significant in Lake Mead. These conclusions appear to have been based primarily on the information that water overlying the sediments in Las Vegas Bay and Las Vegas Wash is aerobic and, therefore, presumably constitutes a sink for phosphorus. This concept derives from the early work of Mortimer (1941, 1942). However, increasing evidence indicates that sediment-to-water phosphorus flux occurs even in aerobic conditions (Syers et al. 1973, Neame 1975). Since no direct measurements of sedimentary phosphorus appear to have been made in Las Vegas Bay, we decided to do so in order to obtain some idea of the type of sediment being deposited and the amount of P which could become available for algal growth upon release from the sediments. These determinations are important in regard to the potential recovery time required for Las Vegas Bay following an eventual reduction of nutrient loading. Of course, detailed measurements of P flux to and from the sediments are required for estimating actual magnitude of internal P loading.

Two short sediment cores were obtained at 10m depth from a small cove in Las Vegas Bay and from Swallow Cove, by SCUBA, in order to compare the sediment characteristics in an area receiving wastewater inflow to one which does not. Additionally, two Ekman dredge samples were taken from 10m depth in Las Vegas Bay. Sampling locations are indicated in Fig. 2. All samples were refrigerated until analysis. The sediment cores were extruded and sectioned at 3cm intervals. After homogenizing each sample by thorough mixing, subsamples were analyzed for water content, organic matter, and available phosphorus.

Sediment wet weight was determined after excess water was removed by draining the sediment samples on absorbent towels for 1 hr. Dry weight was determined after oven-drying of the sediment samples overnight at 105^{o}C. Ash-free dry weight measurements followed sample ignition in a muffle furnace at 500^{o}C for two hours. All weights were measured with a Mettler analytical balance accurate to the nearest 0.1 mg. The following calculations were used to estimate water loss and organic matter content:

$$\% \text{ water content} = \frac{\text{wet wt.} - \text{dry wt.}}{\text{wet wt.}} * 100$$

$$\% \text{ organic matter} = \frac{\text{dry wt.} - \text{ash wt.}}{\text{dry wt.}} * 100$$

Golterman (1977, in press) has recently demonstrated that NTA (Nitrilotriacetic acid) - extractable phosphorus is equivalent to that phosphorus fraction in sediments which is available for algal growth. We used his methodology to estimate available P in Las Vegas Wash sediments. Known amounts of wet sediment from core and Ekman dredge samples were placed in 250 ml Pyrex beakers, stirred vigorously, and extracted overnight in 150 ml of 0.01 M NTA solution (pH 7). The supernatant liquid was pipetted off, filtered through acid-rinsed GFC filters to remove suspended particulate matter, and analyzed for total soluble P and PO_4-P as described in Section V.A.1 above.

6. Nutrient Loading Calculations

As discussed in Section IV above, if models such as Vollenweider's relationship (Vollenweider and Dillon 1974) are to be utilized for the purpose of establishing appropriate water quality criteria for the Las Vegas Wash inflow, they should be applied to Las Vegas Bay (where the problem appears to be most acute) rather than to Boulder Basin. In order to so apply Vollenweider's relationship, it was necessary to calculate the volume of Las Vegas Bay. This was accomplished by constructing a hypsographic curve (surface area versus elevation) and a graph of water volume versus elevation. Three maps were used for this purpose:

a. Lake Mead, Nevada - Las Vegas Wash - Coast and Geodetic Survey Sheet HFP-12-4-63 (inset) - Navy Sheet No. 1, November 1963. Scale 1:12000, Contour interval = 10 ft. showing elevations to 1150 feet only.

b. Las Vegas Bay (i.) Downstream plan profile indicating where 20 cross-sections were drawn. Scale: 1" = 50 ft. vertical, 1" = 1000 ft. horizontal. (ii.) Drawings of the 20 cross-sections of Las Vegas Bay, Scale: 1" = 30 ft. vertical, 1" = 1000 ft. horizontal. These cross-sections were obtained from Clark County Sanitation District No. 1, Waste Treatment Facilities Development Section.

c. Nautical Chart 661-SC. Lake Mead, Arizona-Nevada, U.S. Dept. of Commerce, Scale 1: 48000. This chart shows the 1200 ft. elevation contour.

Surface areas for 12 specific elevation contours (830, 870, 910, 950, 990, and 20-foot intervals from 1030 to 1150) were determined by planimetry using an electronic digitizer. The volume of water between successive contours was estimated by averaging their surface areas and multiplying this average by the distance between contours (e.g., $\frac{Area_{830} + Area_{870}}{2}$ * 40 ft. = volume in cubic feet of water between 830 and 870 ft. elevations). The volume of Las Vegas Bay up to each of the 12 selected elevations was then calculated by summation of partial volumes.

The water volume between 1150 and 1180 ft. elevations was estimated in an analogous way from the cross-sectional maps (b above). The area between 1150 and 1180 ft. was determined by planimetry for each of the relevant cross-sections, and the average of the areas between successive cross-sections was multiplied by the distance between them. These partial volumes were then summed to obtain the 1150 to 1180 ft. water volume. Map c was used to calculate the volume of water between 1150 and 1200 ft. The 1200 ft. contour was planimetered. This area and the 1150 ft. contour area measured on map a were averaged, and the average multiplied by 50 ft. to obtain the volume.

Contour surface areas and water volumes between successive contours were plotted as a function of elevation to permit determination of Las Vegas Bay surface area and volume for any lake level. These values were then used to estimate "permissible" and "dangerous" P loading rates for Las Vegas Bay as described by Vollenweider and Dillon (1974). Results are presented in Section V.B.6.

7. ^{14}C Methodology Experiment

Comparison of the algal productivity estimates of Everett (1972) and Deacon (1976) revealed rather large differences. In addition to making our own productivity estimates, we experimentally examined the possible effect of various acid-rinse treatments on algal productivity estimates. In aquatic systems having reasonably high concentrations of carbonate and a basic pH, the precipitation of $^{14}CO_3$ salts and subsequent trapping of these particulates on filters used in algal productivity measurements can result in anomalously high productivity estimates (Wetzel 1965). A common method of avoiding this source of error is to redissolve any $^{14}CO_3$ precipitates by rinsing the filters with dilute acid. However, some investigators have found that acid rinsing causes rupture of algal cells and results in underestimates of productivity. In order to determine if such methodological artifacts may have produced the discrepancies in previous productivity estimates, we conducted the experiment described below.

From a well-mixed ^{14}C-labelled sample of Lake Mead water, replicate 25 ml subsamples were filtered and exposed to a variety of rinse treatments as listed below:

1 N HCl

0.1 N HCl

0.01 N HCl

0.005 N HCl

0.005 N HCl + 5% Formalin

0.001 N HCl

Distilled Water

No rinse

All rinse treatments were with a 5 ml rinse volume and followed by a distilled water rinsing. Each experimental treatment involved four replicates.

B. Results and Discussion

1. Physical-Chemical Measurements

The results of our survey of physical-chemical factors in Las Vegas Bay and Boulder Basin agree well with previous studies. High conductivity values near the bottom at inner Bay stations reflect the presence of the Las Vegas Wash inflow (Table 2). We did not detect the density current beyond station 3a, although this may be a result of the limited sampling. Temperature and pH measurements are summarized in Tables 3 and 4, respectively. The negative heterograde oxygen curve which has been found consistently by previous investigators was also noted in our study (Table 5).

2. Vertical and Horizontal Patterns of Algal Productivity and Nutrient Concentrations

A synoptic survey conducted at 2 and 5 m depths at 12 stations

TABLE 2

Specific conductivity (micromhos cm^{-1}) at Las Vegas Bay and Boulder Basin stations, 21 September 1976. Station locations are shown in Fig. 2. ERA data.

Depth (m)	Sampling Stations											
	Inner LVB		Las Vegas Bay			Boulder Basin						
	1	2	3	3a	4	5	6	7	8	10	11	12
0	1175	1175	1150	1100	1100	1100	1100	1090	1090	1100	1090	1100
1	1180	1175	1150	1100	1100	1100	1100	1090	1090	1100	1090	1100
2	1200	1175	1150	1100	1100	1100	1100	1090	1090	1100	1090	1100
3	1200	1180	1150	1100	1100	1100	1100	1090	1090	1100	1090	1100
4	1300	1180	1135	1100	1100	1090	1090	1090	1090	1100	1090	1100
5	2150	1180	1140	1100	1100	1080	1090	1090	1090	1100	1090	1100
10		1550	1150	1100	1100	1080	1090	1090	1090	1100	1090	1100
15			1300	1100	1100	1090	1090	1090	1100	1100	1090	1100
20			1950	1200	1100	1100	1090	1090	1090	1100	1100	1100
25				1130	1090	1090	1090	1090	1090	1100	1090	1100
30				1100	1090	1090	1090	1090	1090	1100	1090	1100
35					1100	1090	1090	1090	1090	1100	1090	1100
40					1100	1090	1090	1090	1090	1100	1090	1100
45					1100	1090						
50					1100							
55					1100	1090						
60					1100							
65					1100							
Maximum Depth(m)	6	10	23	31	70	55	130	130	90	60	135	100

TABLE 3

Water temperature (^{o}C) at Las Vegas Bay and Boulder Basin stations, 21 September 1976. Station locations are shown in Fig. 2. ERA data.

Depth	Sampling Stations											
	Inner LVB		Las Vegas Bay			Boulder Basin						
(m)	1	2	3	3a	4	5	6	7	8	10	11	12
0	25.0	25.0	24.6	24.7	24.7	24.5	24.8	24.8	24.8	25.1	24.7	25.1
1	25.0	25.0	25.0	24.8	24.8	24.5	24.8	24.8	25.2	25.0	24.7	25.1
2	25.0	25.0	25.0	24.8	24.8	24.5	24.8	24.8	25.2	24.9	24.7	25.0
3	25.0	25.0	25.0	24.8	24.8	24.5	24.8	24.8	25.1	24.7	24.7	24.8
4	24.6	25.0	25.0	24.8	24.8	24.5	24.7	24.8	25.1	24.7	24.7	24.8
5	24.0	25.0	25.0	24.7	24.8	24.5	24.6	24.8	25.1	24.6	24.7	24.7
10		24.2	24.8	24.6	24.8	24.6	24.5	24.6	25.0	24.6	24.6	24.5
15			24.5	24.5	24.6	24.4	24.5	24.4	24.3	24.4	24.5	24.2
20			23.6	21.2	21.1	21.4	21.2	21.2	21.5	21.4	21.2	21.6
25				18.6	18.6	19.1	18.0	18.4	18.5	18.6	18.6	18.6
30				16.7	16.5	16.6	16.4	16.8	16.4	16.5	16.2	16.7
35					15.0	15.2	15.0	15.0	15.2	15.2	15.2	15.2
40					14.0	14.2	14.0	14.2	14.0	14.2	14.1	14.1
45					13.4	13.3						
50					13.2							
55					12.6	12.6						
60					12.5							
65					12.3							

TABLE 4

pH at Las Vegas Bay and Boulder Basin stations, 21 September 1976. Station locations are shown in Fig. 2. ERA data.

Depth (m)	Inner LVB		Las Vegas Bay			Boulder Basin						
	1	2	3	3a	4	5	6	7	8	10	11	12
0	8.42	8.41	8.38	8.30	8.37	8.32	8.32	8.35	8.35	8.32	8.35	8.32
1	8.42	8.41	8.38	8.30	8.35	8.32	8.32	8.35	8.33	8.32	8.34	8.32
2	8.42	8.38	8.38	8.30	8.35	8.30	8.31	8.35	8.33	8.32	8.32	8.32
3	8.42	8.37	8.38	8.29	8.35	8.31	8.31	8.34	8.33	8.32	8.31	8.32
4	8.42	8.38	8.39	8.28	8.35	8.29	8.31	8.32	8.32	8.32	8.31	8.32
5	8.20	8.38	8.39	8.28	8.34	8.31	8.30	8.31	8.32	8.31	8.30	8.31
10		8.32	8.16	8.25	8.30	8.25	8.18	8.18	8.21	8.24	8.25	8.15
15			7.85	7.96	8.24	8.08	8.06	8.12	7.89	8.13	8.18	8.08
20			7.92	7.35	7.40	7.35	7.36	7.55	7.46	7.35	7.35	7.48
25				7.34	7.38	7.35	7.40	7.48	7.42	7.35	7.35	7.50
30				7.38	7.45	7.42	7.41	7.42	7.49	7.40	7.42	7.50
35					7.48	7.52	7.52	7.55	7.53	7.52	7.57	7.50
40					7.60	7.65	7.61	7.62	7.62	7.62	7.62	7.61
45					7.65	7.68						
50					7.62							
55					7.65	7.73						
60					7.69							
65					7.68							

TABLE 5

Dissolved oxygen concentrations (mg l^{-1} or ppm) at Las Vegas Bay and Boulder Basin stations, 21 September 1976. Station locations are shown in Fig. 2. ERA data.

Depth	Sampling Stations											
	Inner LVB		Las Vegas Bay			Boulder Basin						
(m)	1	2	3	3a	4	5	6	7	8	10	11	12
0	9.30	9.02	9.45	8.57	9.27	9.43	9.52	9.75	9.95	9.08	9.62	9.28
1	9.22	9.00	9.20	8.50	9.22	9.33	9.51	9.66	9.75	9.00	9.54	9.20
2	9.13	8.82	9.08	8.48	9.18	9.25	9.31	9.58	9.65	9.00	9.42	9.12
3	9.10	8.68	9.00	8.41	9.11	9.17	9.22	9.47	9.58	8.95	9.35	9.12
4	9.22	8.65	9.02	8.36	9.08	9.12	9.18	9.40	9.52	8.91	9.30	9.10
5	9.08	8.62	8.78	8.38	9.00	9.10	9.15	9.23	9.45	8.82	9.20	9.08
10		8.60	7.36	8.27	8.61	8.42	7.82	7.95	8.15	8.47	8.37	7.75
15			5.20	6.32	8.30	7.22	6.91	7.52	5.92	7.55	7.90	7.22
20			6.90	2.00	2.41	2.32	2.65	4.16	3.35	2.35	2.52	2.78
25				1.82	2.33	2.25	2.65	3.43	3.20	2.32	2.30	2.65
30					3.00	2.75	2.73	3.28	3.09	2.71	3.10	2.70
35					3.20	3.92	3.70	3.60	3.92	3.56	3.70	3.35
40					4.35	4.98	4.65	4.80	5.00	4.80	4.55	4.85
45					5.15	5.75						
50					5.08							
55					5.32	6.20						
60					5.70							
65					5.87							

throughout Las Vegas Bay and Boulder Basin generally verified the results of previous workers. Algal productivity correlated well with nitrogen and phosphorus concentrations at 2m, as both decreased with increasing distance from Las Vegas Wash. However, 5m samples were considerably less productive beyond station 1 despite high nutrient concentrations at the inner Bay stations (Fig. 3). Vertical profiles of ^{14}C uptake (Fig. 4) show that algal productivity decreases rapidly below 5m with the lower limit of production at about 20m. Light transmission drops sharply in the upper 5m of water in both Las Vegas Bay and Boulder Basin (Fig. 5). Inner Las Vegas Bay had the highest light extinction, reflecting high turbidity due to the combination of relatively dense algal cell density and suspended silt load. Secchi disc transparency progressively increased to Station 4, but was rather constant throughout Boulder Basin (Fig. 6). Algal productivity at or below 5m in Las Vegas Bay is probably more limited by light than nutrient availability.

Although previous investigators have implicated phosphorus as the nutrient most responsible for excessive algal production in Las Vegas Bay, their methods have not provided a satisfactory analysis of orthophosphate phosphorus (PO_4-P), the phosphorus form most available for algal uptake. Everett (1972) and Deacon (1976) have been most directly concerned with relating nutrient concentrations to algal productivity in Lake Mead. Everett failed to describe his methods for PO_4-P analysis. His Figure 27 (p. 79, Everett 1972) indicated an orthophosphate concentration of approximately 20 ug l^{-1} at 5m in Boulder Basin during Septem-

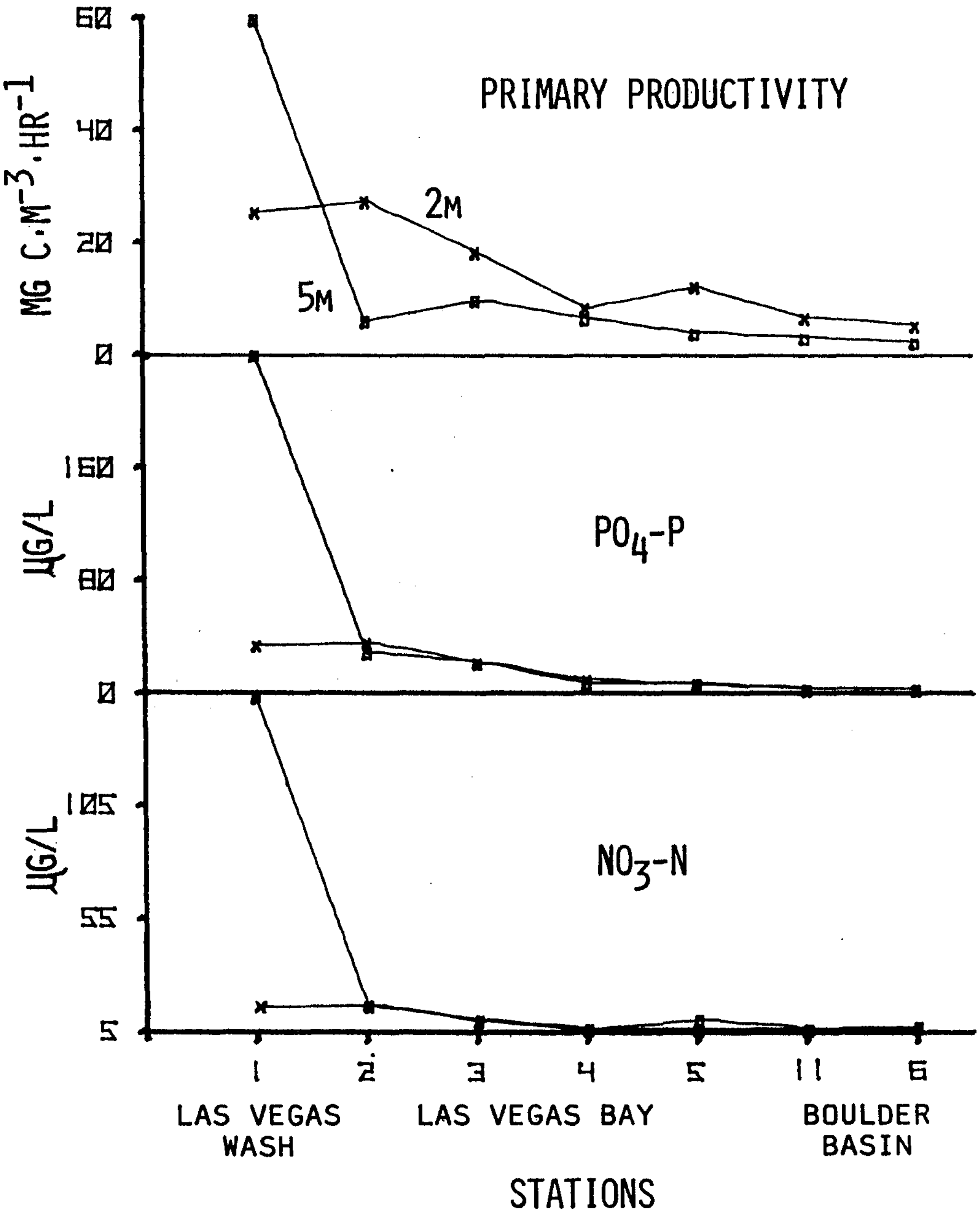

Figure 3. Comparison of algal productivity, NO_3-N and PO_4-P concentrations at 2 m and 5 m along a transect from inner Las Vegas Bay to Boulder Basin, 21 September 1976. ERA data.

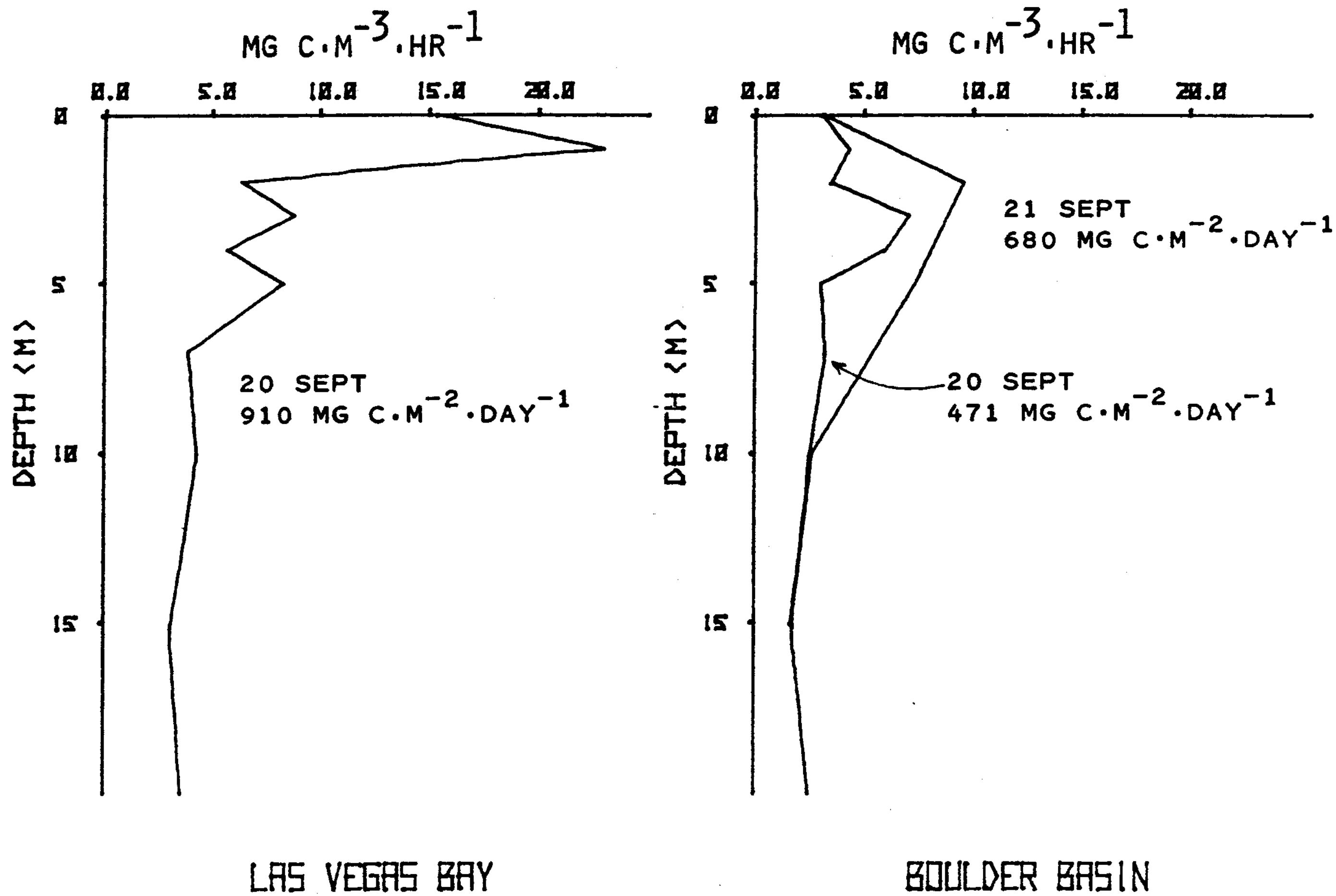

Figure 4. Vertical profiles of algal productivity in Las Vegas Bay and Boulder Basin. Units are mg C m^{-3} per hour of incubation period. Total solar radiation was 324 langleys on 20 September 1976 and 448 langleys on 21 September 1976. ERA data.

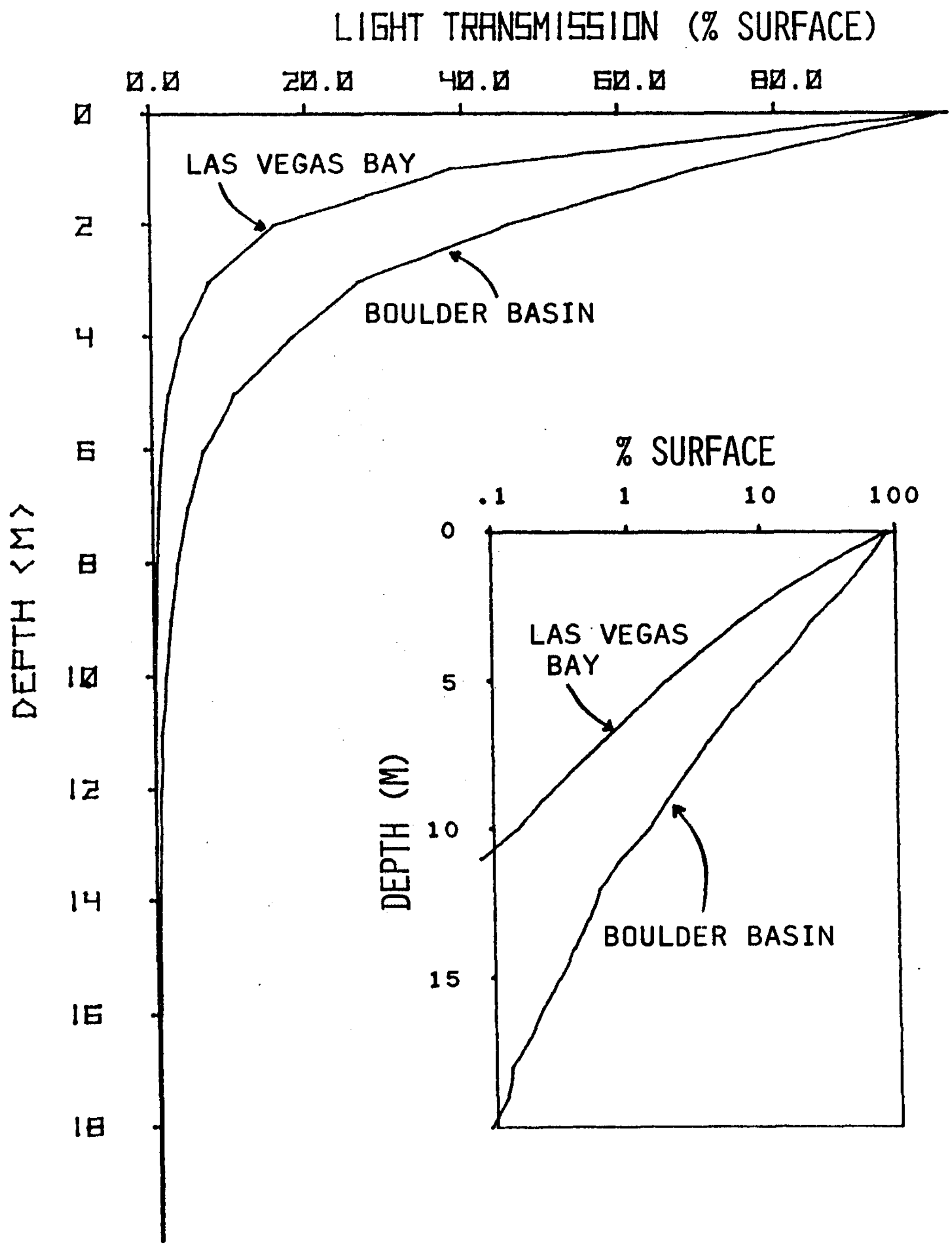

Figure 5. Vertical profiles of relative light penetration in Las Vegas Bay and Boulder Basin, 21 September 1976. Note that light penetration is plotted on a linear scale on the larger axis and a logarithmic scale on the insert. Subsurface values are in % surface light as measured by a deck cell. ERA data.

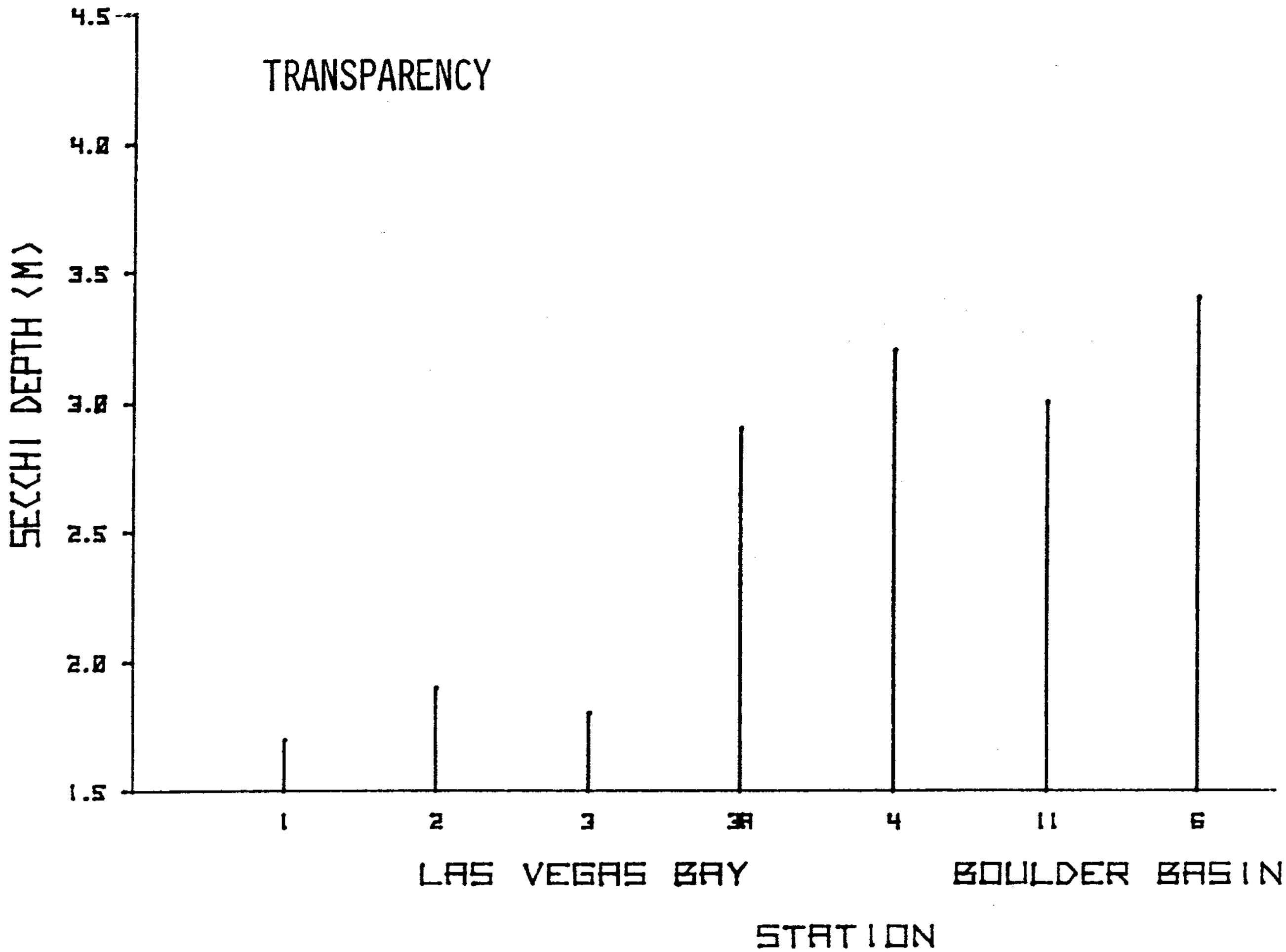

Figure 6. Water transparency, as measured by Secchi disc, along a transect from inner Las Vegas Bay to Boulder Basin, 21 September 1976. ERA data.

ber 1970, but no values are given for Las Vegas Bay. Deacon (1976) reported values for "dissolved P", which by the analytical methods used by EPA (Mullins et al. 1975) is equivalent to total dissolved P; i.e., dissolved organic P plus PO_4-P. In order to determine specifically the forms of phosphorus present in Las Vegas Bay and Boulder Basin, we analytically fractionated our samples into total P (TP), total dissolved P (TSP), and PO_4-P. Particulate P (= TP - TSP) and dissolved organic P (= TSP - PO_4-P) were estimated by difference.

In addition to the previously noted inverse relationship between nutrient concentrations and distance from Las Vegas Wash, our analyses indicate that virtually all of the dissolved phosphorus is in the form of orthophosphate (Tables 6 & 7). The very low levels of dissolved organic P (DOP) present suggest that rapid heterotrophic transformation of DOP to PO_4-P is occurring. Rapid phosphorus cycling is characteristic of lake systems (Rigler 1956, 1964; Lean 1973). The rate of phosphorus cycling is an important consideration since rather high algal productivity can be maintained on a relatively low nutrient pool provided that the rate of P regeneration is high. This appears to be the case in Boulder Basin where algal productivity is moderately high, yet the soluble P pool is low.

Phosphorus concentrations did not change significantly with depth at either Station 4 in Las Vegas Bay or the Bureau raft (Station 12) in Boulder Basin. However, nitrate concentrations increased markedly at 15-20m at both stations (Table 7). Deacon (1972, 1976) also noted a sharp increase in NO_3 and NH_3 nitrogen at these depths. These peaks

TABLE 6

Nitrogen and phosphorus concentrations ($\mu g\ l^{-1}$ or ppb) at Las Vegas Bay and Boulder Basin stations, 21 September 1976. Station locations are shown in Fig. 2. ERA data.

Concentration ($\mu g\ l^{-1}$)	Depth (m)	Sampling Stations: Inner LVB 1	2	Las Vegas Bay 3	3a	4	Boulder Basin 5	6	7	8	10	11	12
NO_3-N	0												6
	2	16	17	10	6	6	8	7	7	7	7	6	8
	5	153	16	10	6	10	7	7	7	6	6	6	6
	10												8
	15												58
Total P	0												7
	2	61	43	28	14	12	9	8	10	6	8	8	9
	5	294	42	27	14	12	10	9	10	7	8	10	7
	10												8
	15												8
Total Sol. P	0												4
	2	35	48	23	11	7	5	5	3	3	3	4	3
	5	239	31	23	6	7	4	3	4	2	3	4	3
	10												3
	15												3
PO_4-P	0												3
	2	34	36	22	10	6	4	3	2	2	2	3	3
	5	240	29	22	7	7	2	3	2	1	4	3	2
	10												3
	15												3

TABLE 6, ERA data, continued

Concentration ($\mu g\ l^{-1}$)	Depth (m)	Sampling Stations: Inner LVB 1	Inner LVB 2	Las Vegas Bay 3	Las Vegas Bay 3a	Las Vegas Bay 4	Boulder Basin 5	Boulder Basin 6	Boulder Basin 7	Boulder Basin 8	Boulder Basin 10	Boulder Basin 11	Boulder Basin 12
(Partic. P)	0												3
	2	26	0	5	3	5	4	3	7	3	5	4	6
	5	55	9	4	8	5	6	6	6	5	5	6	4
	10												5
	15												5
(DOP)	0												1
	2	1	12	1	1	1	1	2	1	1	1	1	0
	5		2	1	0	0	2	0	2	1	0	1	1
	10												0
	15												0

TABLE 7

Comparison of nitrogen and phosphorus concentrations (µg l^{-1} or ppb) in vertical series water samples from the mouth of Las Vegas Bay (Station 4) and mid-Boulder Basin (Station 12), 20 September 1976. See Fig. 2 for station locations. ERA data.

Depth	NO_3-N		Total P		Total Sol. P		Partic. P		PO_4-P		Diss. Org. P	
(m)	LVB	BB	LVB	BB	LVB	BB	LVB	BB	LVB	BB	LVB	BB
0	7	9	9	5	5	23	4	-	5	8	0	-
1	7	6	9	7	6	7	3	0	3	3	3	4
2	6	6	10	6	6	6	4	0	4	2	2	4
3	6	7	10	7	6	6	4	1	4	3	2	3
4	5	7	10	8	4	5	6	3	4	2	0	3
5	6	6	11	5	5	4	6	1	6	2	0	2
7	5	5	10	7	6	6	4	1	6	3	0	3
10	5	6	9	6	6	6	3	0	5	2	1	4
15	60	80	10	6	5	5	5	1	6	4	0	1
20	180	210	12	5	9	6	3	0	6	3	3	3

probably result from ammonification of organic compounds followed by nitrification, and may be associated with the metalimnetic oxygen minimum.

3. Nutrient Enrichment Bioassay Experiments

Systematic nutrient enrichment bioassay experiments were conducted on water samples from inner Las Vegas Bay and Virgin Basin. These locations were chosen in order to compare the effect of nitrogen and phosphorus enrichment on an area receiving wastewater inflow (Las Vegas Bay) and one relatively unaffected by wastewater inflow (Virgin Basin). Virgin Basin water was unexpectedly high in nutrients and therefore somewhat unrepresentative of conditions in Boulder Basin where nutrient levels are considerably lower (Table 7). Nevertheless, additions of Millipore-filtered wastewater (collected from Las Vegas Wash, North Shore Road) to Virgin Basin samples substantially increased algal growth (Fig. 7). Additions of know concentrations of NO_3-N and PO_4-P alone, and in combination, also produced a marked increase in algal growth (Fig. 8). Experimental nitrate enrichment of inner Las Vegas Bay water also stimulated algal productivity, at the 0.2 mg l^{-1} level. Higher additions were inhibiting and phosphate addition appears to reduce the inhibition (Fig. 9). Microscopic examination of subsamples showed that algal species composition remained stable during the bioassay experiments. It must be realized that these experiments reflect the status of the nutrient-phytoplankton interrelationship at only one point in time and therefore only tentative conclusions can be drawn. However, they do suggest that both NO_3-N and PO_4-P, either singularly or in combination, are capable of limiting algal productivity in Virgin Basin near-surface

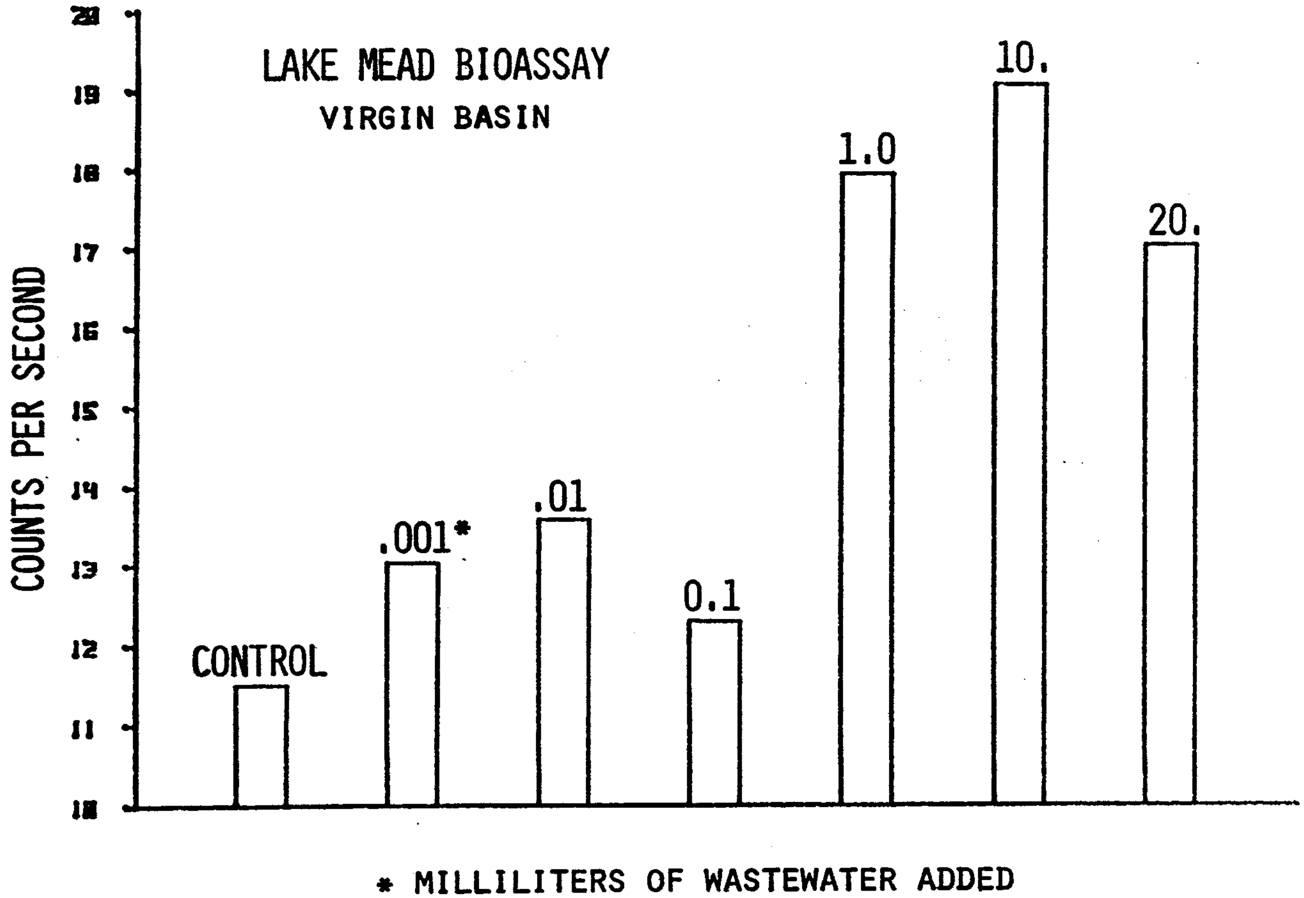

Figure 7. Effect of experimental wastewater additions on algal productivity in Virgin Basin water, 20-23 September 1976, ERA data.

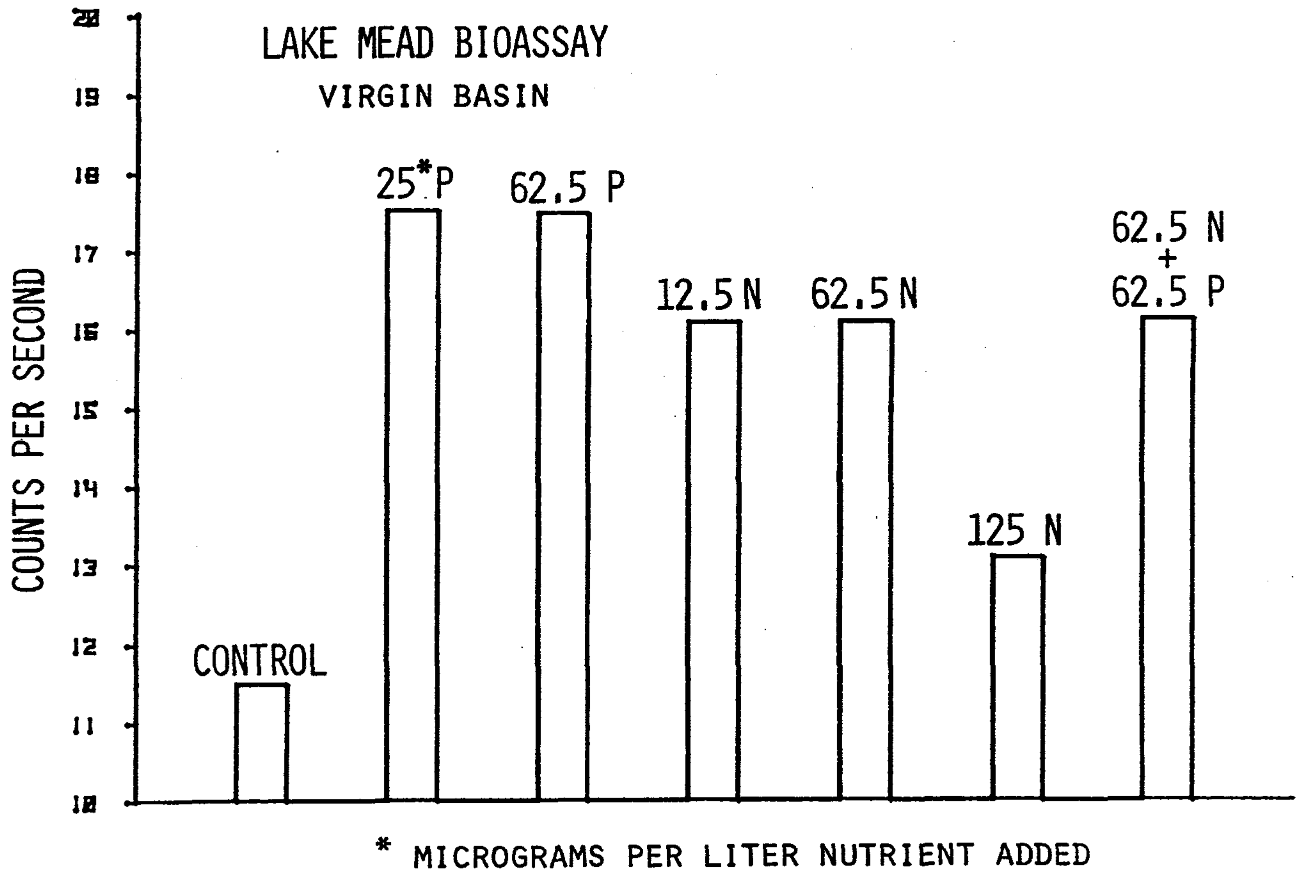

Figure 8. Effect of experimental nitrogen (NO_3-N) and phosphorus (PO_4-P) additions on algal productivity in Virgin Basin water, 20-23 September 1976, ERA data.

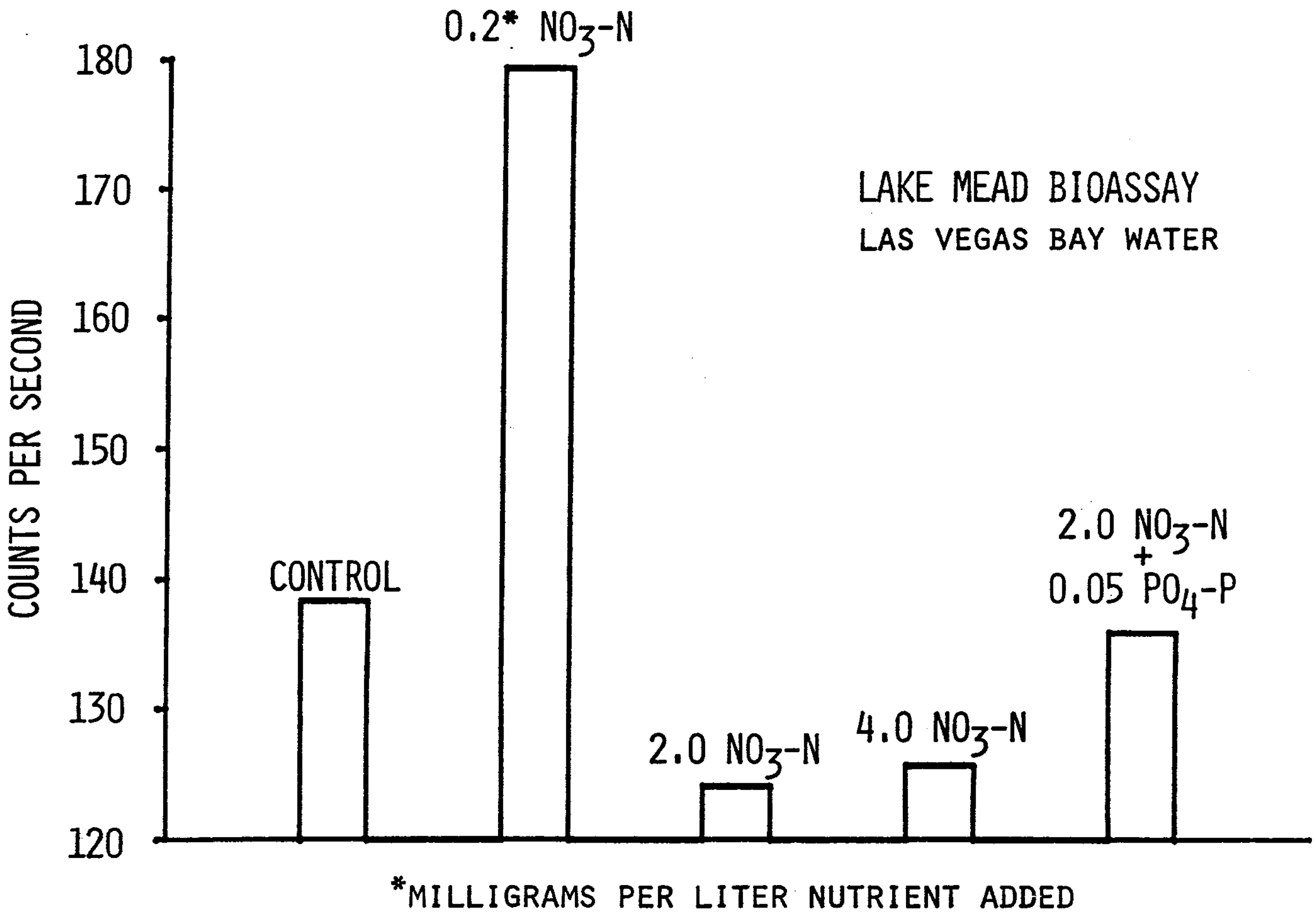

Figure 9. Effect of experimental nitrogen (NO_3-N) and phosphorus (PO_4-P) additions on algal productivity in Las Vegas Bay water, 20-23 September 1976. ERA data.

water. Presumably, the stimulation of Boulder Basin water would have been even more dramatic due to much lower nitrate and orthophosphate concentrations there (Tables 6 & 7). Nitrate is likely to be the most limiting nutrient in inner Las Vegas Bay, due to the high phosphorus loading of that area. Additional bioassay is needed.

It is interesting to compare the conclusions drawn from our limited series of nutrient bioassay experiments with those of Deacon (1976) based on N:P ratios. The concept underlying the use of N:P ratios as a procedure for assessing nutrient availability in aquatic systems is based on the comparison of the N and P content of plant tissues to that of the surrounding water. An N:P ratio of approximately 7 or 8 : 1 (by weight) is generally considered an average or typical value for freshwater algae and macrophytes (Vallentyne 1974). A lesser value, therefore, implies a nitrogen deficiency while a larger value implies a phosphorus deficiency in the surrounding medium. In his Table 10, Deacon (1976) presented N:P ratios for Las Vegas Bay and Boulder Basin stations based on 1975 water chemistry data. From the very low values obtained, he concluded that phosphorus is in excess and "nitrogen is in short supply for most of the year in Las Vegas Bay and during the summer in Boulder Basin". There are several serious problems with Deacon's analysis.

(i.) The 8:1 N:P ratio for aquatic plant tissue is a reasonable <u>average</u> or <u>typical</u> value; however, the elemental composition of an organism varies over a wide range in response to the composition of its environment (Gerloff 1969) and in a specific case, an <u>average</u> or <u>typical</u> value should not be relied upon as a criterion in the absence of more direct evidence (e.g., tissue analysis of Lake Mead algae on a seasonal basis).

(ii.) Although the possibility of assessing the nutrient status of water bodies by chemical analysis of water samples is appealing, numerous uncertainties exist in analytical sensitivity at low concentrations and in the correspondence of amounts measured chemically with amounts actually available biologically. An examination of the water chemistry data in Appendix I of Deacon (1976) indicates that concentrations of NH_3-N, NO_3 + NO_2-N, PO_4-P, and total N were often at or below the level of sensitivity of the analytical methods used. Such uncertainties, in addition to the presence of nitrogen-fixing algae (e.g., *Anabaena* sp.) and the ability of many algae to store phosphorus, make the N:P ratio approach to identifying nutrient deficiencies unreliable.

(iii.) Assuming an N:P ratio of 8 to be valid for Lake Mead algae and the chemical analyses to be entirely accurate, a remaining serious problem is Deacon's method of ratio calculation; the numerator of his ratio is the sum of NH_3, NO_3, and NO_2 nitrogen while the denominator is total phosphorus. The comparison of a part (dissolved inorganic nitrogen) to a whole (total phosphorus) is invalid, and the division of the first by the second ensures an anomalously low value for the quotient. From the water chemistry data in Appendix I of Deacon (1976) we recalculated N:P ratios by three methods:

(a.) dissolved inorganic N ÷ total P; i.e., Deacon's method,

(b.) dissolved inorganic N ÷ dissolved inorganic P, and

(c.) total N ÷ total P.

Comparison of the recalculated ratios is presented in Table 8. The latter two methods listed above are more valid comparisons and their generally higher quotients imply a very different conclusion in regard to nutrient availability in Lake Mead. By the same 8:1 criterion used by Deacon (1976), only inner Bay stations (Stations 1 and 2) may be interpreted to be N-limited. Other Las Vegas Bay stations (3 and 4) and Boulder Basin stations (5 and 6) have high N:P values and therefore, may be considered to be generally more P than N deficient.

The use of N:P ratios for detecting nutrient limiting factors is rather indirect, and therefore should be avoided especially as a basis for important decisions regarding water quality strategies. Nutrient enrichment bioassays provide a much more direct technique which can experimentally answer specific questions regarding nutrient limiting factors. For adequately assessing the situation in Las Vegas Bay and Boulder Basin, an extensive series of nutrient bioassay experiments should be conducted to define the seasonal aspects of nutrient limitations, the possible interaction of other nutrients with P and N in controlling algal productivity, the response of specific bloom organisms to various nutrient factors, and the specific comparison of the effects of various wastewater treatments on algal productivity.

TABLE 8

Comparison of N:P ratio values calculated as $NH_3 + NO_3 + NO_2$-N ÷ total P (IN/TP), $NH_3 + NO_3 + NO_2$-N ÷ PO_4-P (IN/IP), and total N ÷ total P (TN/TP). Values represent monthly averages calculated from the data of Appendix I, Deacon (1976). IP is an overestimate; no PO_4-P data were reported, so total soluble P values were used as an approximation of IP.

	Station 1			Station 2			Station 3		
Date	IN/TP	IN/IP	TN/TP	IN/TP	IN/IP	TN/TP	IN/TP	IN/IP	TN/TP
April	1.6	1.7	0.2	0.7		5.8	4.5	12.1	13.2
May	2.6	2.2	0.2	1.5	4.6	7.5	9.0	18.1	13.0
June	2.2	2.5	0.2	1.2	1.4	7.2	2.3	2.5	13.7
July	2.8	3.4	0.4	2.5	3.4	11.8	0.4		8.7
August	0.3	0.3	0.3	1.8	2.6	7.0	8.3	11.2	13.8
Sept.	1.5	18.1	0.6	1.6	2.7	8.2	2.2	2.2	11.1
Oct.	1.9	1.9	0.2	2.5	4.1	7.8	2.0	4.8	7.6
Nov.	2.6	2.8	0.2	9.1	10.6	7.4	6.7	15.7	6.1
Dec.	3.4	3.4	0.4	10.0		11.1	12.0	30.0	8.0
Jan.	2.9	3.1	0.6	8.1	8.1	18.8	11.3	26.9	6.4
Feb.			0.6			9.1			8.7
Average	2.2	3.9	0.4	3.9	4.7	9.2	5.9	13.7	10.0

TABLE 8, continued

Date	Station 4			Station 5			Station 6		
	IN/TP	IN/IP	TN/TP	IN/TP	IN/IP	TN/TP	IN/TP	IN/IP	TN/TP
April	15.9	30.0	17.6				14.7	56.0	10.5
May	13.3	24.6	18.0	10.4	11.2	14.8	14.8	36.7	20.8
June	6.1	9.2	25.1	7.7	10.0	38.4	8.2	23.3	27.3
July	3.5	4.4	17.6	5.7	11.2	25.4	3.8	6.7	25.0
August	3.2	5.9	22.7	3.6	5.0	18.2	5.0	7.3	27.8
Sept.	2.5	1.3	>12.5				4.0	3.3	20.0
Oct.	4.3	11.6	14.7	5.9	13.1	27.4	4.7	15.6	15.8
Nov.	11.0	33.3	10.0	11.4	27.8	9.1	11.4	34.3	9.5
Dec.	15.8	30.0	10.5	17.2	28.2	11.1	13.6	37.5	9.1
Jan.	13.6	24.3	8.0	10.0	30.0	66.7	14.2	24.3	12.5
Feb.			7.1			71.4			7.7
Average	8.9	17.5	14.9	9.0	17.1	31.4	9.4	24.5	16.9

4. Phytoplankton Identification and Enumeration

Results of the examination of phytoplankton samples collected from stations throughout Las Vegas Bay and Boulder Basin are summarized in Table 9. *Ankistrodesmus falcatus* var. *spirilliformis* was the dominant species at all stations. At inner bay stations, the sub-dominant algae were *Cyclotella chaetoceras*, *Merismopedia tenuissima*, and *Raphidiopsis curvata*. Boulder Basin stations had subdominance positions occupied by *Oscillatoria* sp., *Raphidiopsis curvata*, and *Raphidiopsis* sp. Inner bay station had approximately 3000 cells ml^{-1}, while the remaining stations ranged from 2000 to 5000 cells ml^{-1}. Phytoplankton samples from the Virgin Basin were dominated by the same species as in Boulder Basin, but cells were much less numerous (ca. 500 cells ml^{-1}).

In general, we found no great differences in the phytoplankton communities of Las Vegas Bay and Boulder Basin. Both were dominated by *Ankistrodesmus* with subdominance by filamentous blue-green algae and diatoms. *Anabaenopsis circularis*, *Anabaena sp.*, and other nitrogen-fixing algae were present in low numbers. Bluegreens were more abundant in the Basin and had heterocysts which indicate that they are capable of nitrogen fixation.

5. Sediment Analysis

Results of sediment analysis are presented in Table 10 for Las Vegas Bay samples and Table 11 for the Swallow Cove sediment core. Profiles of water content, organic matter, and NTA-extractable P are compared in Fig. 10. The sediments examined ranged from coarse sand to clay texturally, and are relatively low in organic content. In all samples, virtually all of the NTA-extractable P was in the form of

TABLE 9

Phytoplankton species composition and cell densities (cells ml^{-1}) at Las Vegas Bay and Boulder Basin stations, 21 September 1976. See Fig. 2 for station locations. ERA data.

	Sampling Stations										
	Las Vegas Bay				Boulder Basin						
	2	3	3a	4	5	6	7	8	10	11	12
CHLOROPHYCEAE (Green Algae)											
Ankistrodesmus	1868	2358	731	1689	1538	1462	1236	1142	1358	1406	1745
Chlamydomonas	68	47	0	9	0	0	0	0	0	0	0
Carteria	42	57	9	9	0	0	9	19	0	0	0
Tetraedron	42	38	28	19	38	0	19	9	9	38	85
Scenedesmus abundans	11	9	0	0	0	0	0	0	0	0	0
Scenedesmus acuminatus	4	0	0	0	0	0	0	0	0	0	0
Micractinium	4	0	5	0	0	0	0	0	0	0	0
Oocystis	4	0	0	0	0	0	9	0	0	0	0
Pandorina	0	19	5	0	0	0	0	0	0	0	0
Chlorophyceae subtotal	2043	2528	778	1726	1576	1462	1255	1170	1367	1444	1830
CYANOPHYCEAE (Blue-Green Algae)											
Merismopedia	283	330	57	47	19	94	132	9	94	57	19
Raphidiopsis curvata	155	292	302	915	642	745	670	613	1255	934	774
Raphidiopsis (straight)	0	0	396	821	519	642	453	406	500	717	623
Anabaena	64	189	5	179	19	47	47	38	19	283	38
Microcystis	57	38	0	0	0	0	9	19	0	0	0
Lyngbya	53	9	5	0	0	0	9	0	0	9	19
Oscillatoria	23	19	335	1113	1160	953	1085	1245	1094	783	802
Anabaenopsis	0	0	66	0	132	57	132	47	217	0	226
Marssoniella	4	0	0	0	0	0	0	0	0	0	0
Spirulina	0	0	0	0	9	0	0	0	0	0	0
Aphanothece microspora	0	0	0	0	0	0	0	0	38	19	28
Cyanophyceae subtotal	639	877	1166	3075	2500	2538	2537	2377	3217	2802	2529

TABLE 9, ERA data, continued

	Sampling Stations										
	Las Vegas Bay				Boulder Basin						
	2	3	3a	4	5	6	7	8	10	11	12
BACILLARIOPHYCEAE (Diatoms)											
Anomoeneis vitrea	4	28	33	9	47	28	66	94	85	47	47
Cyclotella	321	557	90	160	0	0	19	57	66	9	94
Synedra radians	11	0	0	0	0	0	0	0	0	0	0
Fragilaria crotonensis	4	19	0	0	9	0	0	0	0	0	0
Bacillariophyceae subtotal	340	604	123	169	56	28	85	151	151	56	141
DINOPHYCEAE (Dinoflagellates)											
Glenodinium	15	19	5	0	0	0	0	0	0	0	0
Peridinium	4	9	0	9	0	0	0	28	9	0	0
Gymnodinium	0	0	0	0	0	0	0	0	9	0	0
Dinophyceae subtotal	19	28	5	9	0	0	0	28	18	0	0
CRYPTOMONADACEAE (Cryptomonads)											
Cryptomonas	34	19	19	19	0	9	38	9	28	0	9
CHRYSOPHYCEAE (Yellow-Brown Algae)											
Mallomonas	19	0	5	38	0	0	19	28	0	0	9
EUGLENOPHYTA (Euglenoids)											
Euglena	8	0	0	0	0	9	0	9	0	9	0
Total Cells ml^{-1}	3102	4056	2096	5036	4132	4046	3934	3772	4781	4311	4518

TABLE 10

Analytical results for sediment core and Ekman dredge samples from Las Vegas Bay. All samples obtained from water depth of approximately 10 m. ERA data, Sept. 1976.

Sediment Depth (cm)	% Water	% Organic Matter	Total Extr. P (μg P/ g Wet Sed.)	Extr. PO_4-P (μg PO_4-P/ g Wet Sed.)	% PO_4-P of Total Extr. P
SEDIMENT CORE:					
0-3	26.4	2.8	8.63	8.33	97
3-6	30.4	2.6			
6-9	28.3	1.1	11.09	11.62	100
9-12	26.3	3.2			
12-15	26.7	2.6	9.95	9.56	96
15-18	28.4	2.6			
18-21	26.9	2.0	13.03	12.64	97
EKMAN DREDGE SAMPLES:					
Station 1	37.4	3.3	134.87	86.28	64
Station 2	42.0	4.0	190.52	186.38	98

TABLE 11

Analytical results for sediment core from Swallow Cove. Core taken from 10 m water depth. ERA data, Sept. 1976.

Sediment Depth (cm)	% Water	% Organic Matter	Total Extr. P (μg P/ g Wet Sed.)	Extr. PO_4-P (μg PO_4-P/ g Wet Sed.)	% PO_4-P of Total Extr. P
SEDIMENT CORE:					
0-2	38.0	3.7	9.27	8.89	96
2-5	37.9	4.6			
5-8	28.3	2.8	8.98	8.81	98
8-11	34.3	3.9			
11-14	35.0	4.7	10.94	10.80	99
14-17	38.1	5.5			
17-20	29.2	3.5	14.26	14.29	100
20-23	23.4	2.8			
23-26	20.2	1.9	12.56	12.54	100
26-29	13.5	1.1			
29-31	14.9	1.4	13.25	12.95	98

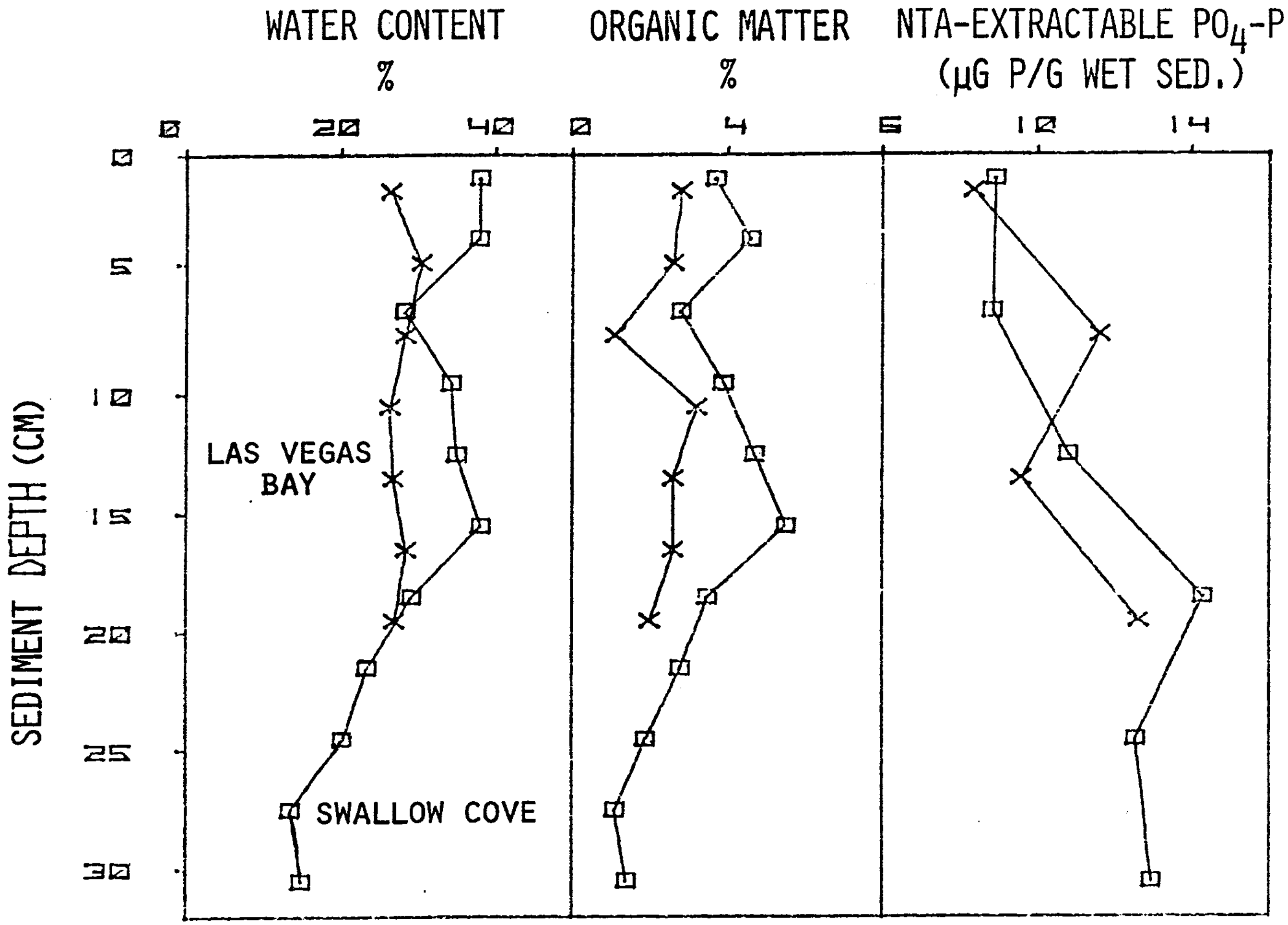

Figure 10. Vertical profiles of water content, organic matter, and NTA-extractable phosphorus for Las Vegas Bay and Swallow Cove sediment cores, 21 September 1976. ERA data.

orthophosphate (Tables 10 and 11). Swallow Cove sediments were slightly higher than Las Vegas Bay samples in water and organic content, but the two were comparable in NTA-extractable P levels (Fig. 10). Ekman dredge samples from Las Vegas Bay stations 1 and 2, near the Las Vegas Wash inflow, were higher in water and organic content than the Las Vegas Bay core sample. Orthophosphate comprised a considerably smaller fraction of the NTA-extractable P at Station 1 whereas at Station 2, 98% of the extractable P present was PO_4-P.

The low organic content of Las Vegas Bay sediments is most reasonably attributed to the diluting effect of the Las Vegas Wash silt load rather than low organic production within Las Vegas Bay. That NTA-extractable P levels are comparable in the two locations, despite the lower organic content of the Las Vegas Bay core, points to the greater nutrient loading of Las Vegas Bay and suggests that sorption of PO_4-P by sedimenting silt particles may be occurring. The larger amount of extractable P in the Ekman dredge sample at station 1 as compared to that at station 2 further indicates that phosphorus is being lost by sedimentation. This, of course, is an important factor in the estimation of permissible loading rates and in the amount of time required for recovery following a reduction in nutrient loading.

6. Nutrient Loading Calculations

In order to apply Vollenweider's relationship to Las Vegas Bay, the parameters in Table 12 were calculated assuming a lake surface level of 1180 feet (elevation as of September 1976). On this basis, the "permissible" loading rate (L_p) = ca. 0.18 g P $m^{-2}yr^{-1}$ and the

TABLE 12

Parameters used in estimation of "permissible" and "dangerous" loading rates for Las Vegas Bay. ERA data. Sept. 1976.

Parameter			Source
1. Surface Area	A	26.2×10^6 m^2	See Fig. 11
2. Volume	V	812.8×10^6 m^3	See Fig. 12
3. Mean Depth	$\bar{z} = \frac{V}{A}$	31.0 m	From 1 and 2
4. Las Vegas Wash Discharge	Q	193,280 m^3 day^{-1} (mean for 1975 water year)	*
5. Residence Time of Water	$\tau_w = \frac{V}{Q}$	11.52 years	From 2 and 4
6. Phosphorus Concentration of Discharge	c	4.53 mg l^{-1} (mean for 1975)	Deacon (1976)
7. Total Phosphorus Loading	$TL = Qxc$	319,579 kg $year^{-1}$	From 4 and 6
8. Areal Loading	$L = \frac{TL}{A}$	12.2 g^P m^{-2} $year^{-1}$	From 7 and 1
9. Mean Depth ÷ Residence Time	$\bar{z}/\tau_w$	2.69 m $year^{-1}$	From 3 and 5

*Source of data: Clark County Sanitation District No. 1, Waste Treatment Facilities Development Section.

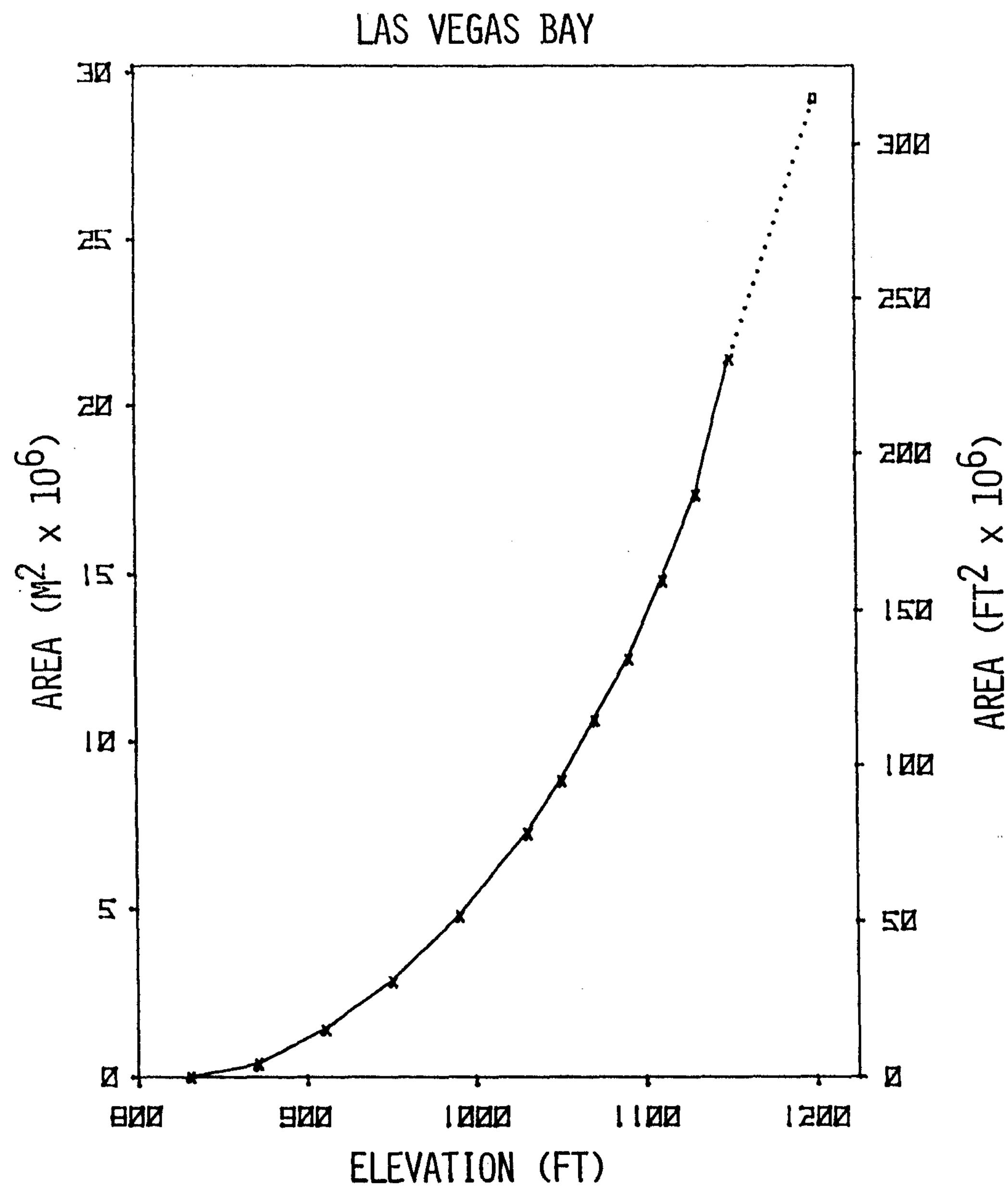

Figure 11. The relationship between surface area and lake surface elevation in Las Vegas Bay. ERA data.

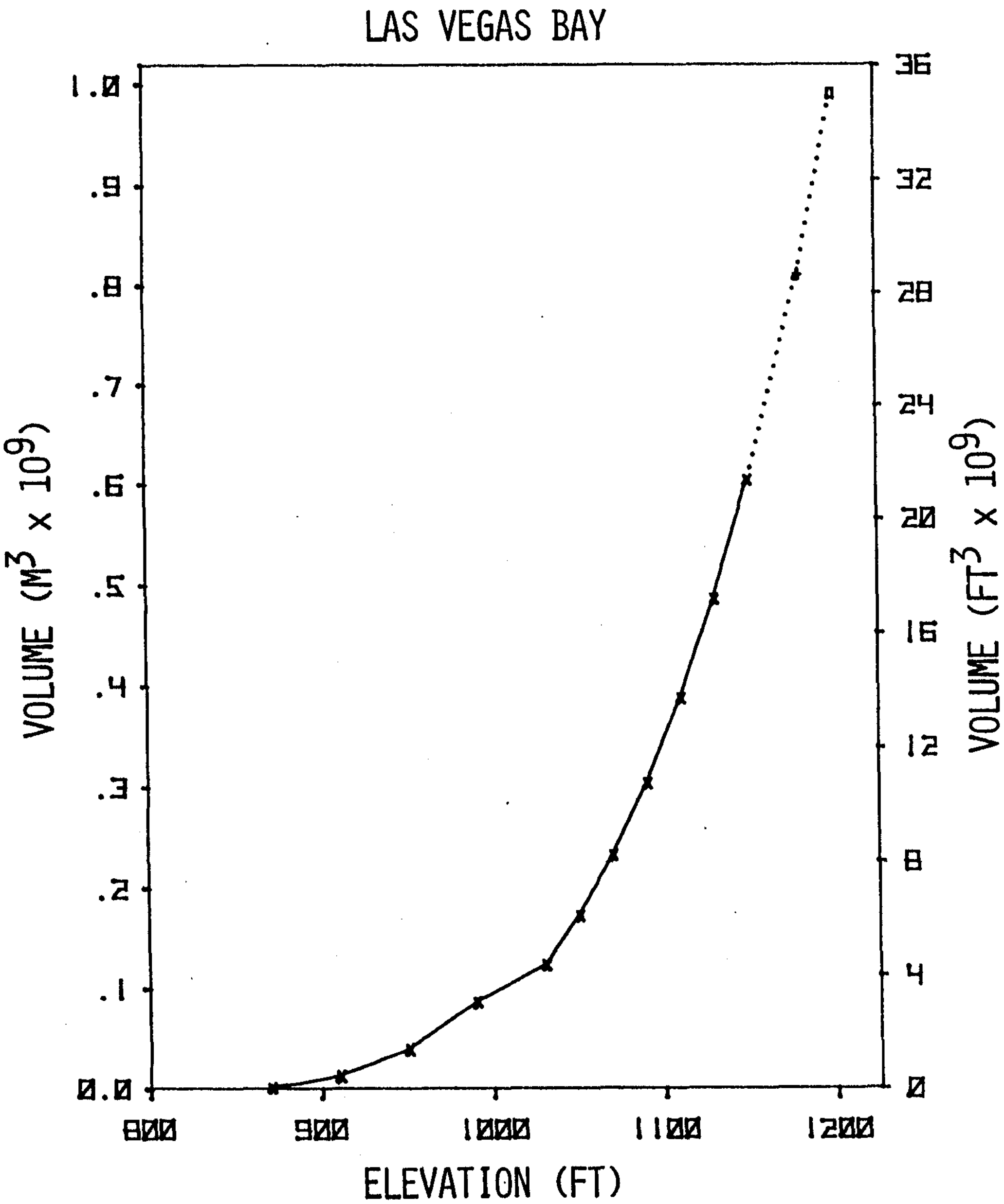

Figure 12. The relationship between water volume and lake surface elevation in Las Vegas Bay. ERA data.

"dangerous" loading rate (L_d) = ca. 0.35 g P m^{-2} yr^{-1} (see Fig. 2, Vollenweider and Dillon 1974). The present loading rate from Las Vegas Wash is 875 kg P day^{-1}, which is equivalent to a specific loading rate of 12.2 g P m^{-2} yr^{-1}. Thus, the present specific loading rate exceeds the calculated "permissible" loading rate 67 times and the "dangerous" loading rate 34 times. If the present Las Vegas Wash discharge volume were maintained, the effluent would have to contain less than 0.067 mg P l^{-1} to attain the calculated L_p and thereby return the Bay to a more desirable trophic level. This represents a 98.5% reduction in the mean P concentration of the effluent. The National Pollution Discharge Elimination System (NPDES) requirement is an effluent concentration of 0.5 mg P l^{-1}, a 90% reduction of the current loading, which would lower the specific loading rate to 1.3 g P m^{-2} yr^{-1}, over three times the "dangerous" loading rate. Results of a recent AWT design verification study (Nevada Environmental Consultants 1976) prepared for the Clark County Board of Commissioners indicated that lime coagulation, flocculation and sedimentation processess proposed for AWT produced an effluent averaging 0.23 mg P l^{-1}. This represents a 95% reduction of current loading and a specific loading rate of 0.62 g P m^{-2} yr^{-1}, still well in excess of "dangerous" loading.

For the reasons discussed in Section IV of this report, we feel that the application of Vollenweider's relationship may not be particularly appropriate in this situation. However, if further information indicates that application of Vollenweider's relationship is valid, our calculations indicate that AWT technology would not solve the problem in Las Vegas Bay.

Fig. 12 is instructive in regard to the great effect of lake surface level on the volume of Las Vegas Bay. The calculations above were based on a lake level of 1180 ft. and a Bay volume of ca. 8×10^8 m^3 (Table 12). Since the effective nutrient loading increases rapidly with decreasing water volume, slight decreases in lake water level can produce sharp increases in nutrient concentrations and associated problems in Las Vegas Bay. When models such as that of Vollenweider and Dillon (1974) are utilized to establish water quality criteria or to form a basis for pollution abatement decisions, calculations should be based on the lowest projected lake water levels in order to avoid serious water quality problems during periods of decreased water volume.

7. Differences in Algal Productivity Estimates

Neither Everett (1972) nor Deacon (1976) describe their methods of estimating phytoplankton productivity in sufficient detail to permit a rigorous evaluation; therefore, we made independent estimates for purposes of comparison. As shown in Table 13, our productivity estimates are considerably lower than those of both the previous investigators. The cause for this difference in productivity estimates is not apparent at the present time, but could be related to any of the following factors:

(i.) Differences and/or discrepancies in methodology.

This is a very likely possibility, but difficult to evaluate rigorously due to the lack of detailed description of methodology by prior investigators, the short time span and limited scope of our study, and the time difference between the investigations being compared. We

TABLE [illegible]

Comparison of algal productivity estimates (^{14}C method) for Las Vegas Bay and Boulder Basin.

	Algal Productivity (mg C m^{-2} day^{-1})		
Date of Measurement	Las Vegas Bay (Station 4)	Boulder Basin (Bureau Raft)	Investigator
4-11 Sept. 1970	3200	3100	Everett (1972)
Sept. 1974	7080	3056	Deacon (1976)
Sept. 1975	16405	7857	
20 Sept. 1976	910	471	ERA (1976)
21 Sept. 1976		680	

were able to evaluate two important aspects of the methodology: 1) determination of the amount of unlabelled carbon available for algal uptake and 2) possible contamination of filters with ^{14}C-labelled carbonates. The determination of dissolved inorganic carbon concentration is very important in algal productivity estimates, since the ratio of ^{12}C:^{14}C available determines the magnitude of the carbon-uptake rate. As far as could be determined, all investigators have used the same basic technique for this estimate; i.e., measurement of temperature, pH, and total alkalinity (Amer. Pub. Health Assn. 1971) and the conversion tables of Saunders, Trama, and Bachman (1962). The calculated values generally fall in the 20-30 mg C l^{-1} range. Thus even if the absolute value of the estimates were off, the calculated productivity values should still be close if this were the only problem.

Serious overestimation of algal productivity can result if productivity filters become contaminated with ^{14}C-labelled carbonate precipitates. Everett (1972) apparently did not take any precautions to avoid such contamination in his study, although he did indicate that he rinsed down his filtration apparatus in order that all radioactive particles reach the filter. Deacon (1976) rinsed filters with 0.005N HCl + 5% formalin. The most commonly used acid-rinse procedure involves rinsing with 0.1N HCl followed by a distilled water rinse. Our experimental results (Table 14) indicated no significant differences among the treatments used, so this aspect of the methodology provides no explanation for the observed differences in productivity values.

(ii.) Natural variation in algal productivity about some relatively constant mean value.

TABLE 14

Effects of dilute acid rinsing on the activity of ^{14}C-labelled phytoplankton samples from Lake Mead. Results are expressed in counts per minute; four replicates per treatment. ERA data, Sept. 1976.

Treatment	$\bar{x}$	Coefficient of of Variation (%)	$\bar{x} \pm 1$ S.D.
1 N HCl	439	10.3	393 - 484
0.1 N HCl	400	9.3	363 - 436
0.01 N HCl	454	14.5	388 - 520
0.005 N HCl	550	22.2	428 - 672
0.005 N HCl + formalin*	578	18.7	470 - 686
0.001 N HCl	561	9.1	510 - 612
Dist. Water	421	17.5	347 - 494
Unrinsed	427	21.2	336 - 517

*Rinsing technique used by Deacon (1976).

It is certainly possible that the observed differences may only reflect the relatively infrequent measurement of a continually varying phenomenon, and thus be a sampling artifact. The fact that our estimates were based on only two sampling days makes it quite possible that they may be atypical.

(iii.) A real change in the level of productivity.

There appears to be some evidence for this possibility. In his recent testimony before the Sewage and Wastewater Advisory Committee, Deacon noted an apparent reduction in algal productivity since 1972 and suggested that it could be due to increasing lake levels during that time. It appears that nutrient levels in Boulder Basin may have decreased somewhat over approximately the same time period (Table 15). We also noted a similar trend in the severity of the metalimnetic oxygen minimum. The lowest metalimnetic oxygen concentrations were found by Hoffman et al. (1967) and so it appears that the degree of oxygen depletion in the metalimnetic layer may have decreased since at least 1967. If the decomposition of moribund phytoplankton cells accumulated near the thermocline were the major factor producing the metalimnetic oxygen depletion, the magnitude of depletion would be directly related to algal productivity. Based on rather indirect evidence, Deacon and co-workers (1976) concluded that phytoplankton and zooplankton respiration are the primary causative agents of the metalimnetic oxygen depletion. We suggest that a direct experimental approach could lead to different conclusions; e.g., that oxidative decomposition of organic detritus by heterotrophic bacteria is much more important in maintaining the metalimnetic oxygen minimum than previously realized. If we are correct,

TABLE 15

Comparison of nutrient concentrations (mg l^{-1}) reported for Boulder Basin stations since 1966.

Date of Sampling	Sampling Location	Total P	Total Diss. P	PO_4-P	NO_3-N	Source
Nov. 1966	mid-Boulder Basin			0.33	0.27	Hoffman, Tramutt, and Heller (1967)
	Saddle Island			0.33	0.14	
Sept. 1970	Boulder Basin			0.02	2.5	Everett (1972)
April 1971	Boulder Basin			0.03	2.0	
Mar.-Sept. 1974	Saddle Island		0.005-0.044			Deacon (1975)
May-Nov. 1974	Beacon Island	0.011-0.020			0.05-0.23	
Mar.-Dec. 1974	mid-Boulder Basin	0.018			0.12	Deacon (1976)
April-Dec. 1975	mid-Boulder Basin	0.016			0.13	
Sept. 1976	mid-Boulder Basin	0.008		0.003	0.007	ERA (1976)
	Saddle Island	0.009		0.004	0.008	

the decreased severity of the metalimnetic oxygen-depleted layer would further support the possibility that a real decrease in algal productivity may have occurred.

Apparent decreases in nutrient concentrations, algal productivity, and the metalimnetic oxygen deficit all constitute rather obvious contradictions to the increased nutrient (N and P) loading described by Deacon (1976). At the present time, we can only offer some alternative hypotheses to explain these observations:

(a) Nutrients other than nitrogen and/or phosphorus are limiting algal productivity in Las Vegas Bay and Boulder Basin.

(b) The nutrient-rich inflow from Las Vegas Wash proceeds as a density current through Las Vegas Bay and into Boulder Basin without mixing extensively with the overlying water. Depending on its residence time, once in Boulder Basin hypolimnion, most of the Las Vegas Wash inflow probably exits the lake via Hoover Dam without ever mixing with the relatively thin overlying layer of euphotic water. Thus, the nutrient loading of Las Vegas Wash is only indirectly related to the water quality of Las Vegas Bay and Boulder Basin. If this hypothesis is substantive, Lake Mead escapes the full impact of the Las Vegas domestic and industrial wastewater inflow but the problem is transferred downstream.

(c) Lake level increases have diluted Las Vegas Wash effluents, thereby lowering nutrient concentrations and algal productivity in the euphotic zone. If this is the case, the problem is not gone, but merely postponed until the next reduction in lake level.

(d.) Increases in turbidity may have caused a gradual reduction in algal productivity in Lake Mead.

Of course, these are alternative hypotheses for an apparent decrease in algal productivity; they are not statements of fact or conclusions. The implication here is that important questions exist in regard to the actual fate of nutrient inputs, the degree of the effective nutrient loading, trends in long-range productivity and available nutrient levels, and the trophic status of Las Vegas Bay and Boulder Basin.

VI. GENERAL DISCUSSION AND ALTERNATIVE STRATEGIES

In dealing with the water quality of reservoirs, it must be realized that dams are barriers to natural drainage and the water bodies formed above them constitute efficient traps for sediments and nutrients in the inflowing water. Therefore, rather high levels of biological productivity in reservoirs should not be unexpected. This is particularly true for Lake Mead where biological productivity is increased further by high water temperatures and an extended growing season. The problem then becomes a matter of degree rather than an absolute; i.e., when do water quality conditions become objectionable for water users? Obviously, the preferred level of "water quality" varies with the purposes for which the water is used; i.e., what is "good" water to the swimmer and skier is not necessarily considered "good" by the fisherman. Lake Mead is a multi-purpose reservoir (hydroelectric power generation, flood control, irrigation, municipal water source, recreation) and some of these uses inevitably conflict in regard to the preferred water quality conditions.

Vollenweider's input-output approach to the problem of nutrient-loading (Vollenweider and Dillon 1974) is an instructive initial step toward prediction of the eutrophication process. Unfortunately it has been seized as an absolute method for establishing acceptable and unacceptable rates of P loading for situations in which it is not particularly applicable. For several reasons, it appears that Lake Mead is such a situation.

(i.) If Vollenweider's equation is to be applied at all to Lake Mead, in regard to the present situation it should at least be applied to inner Las Vegas Bay where the problem is most severe, rather than to Boulder Basin.

(ii.) At the present time, the knowledge of circulation patterns within both Las Vegas Bay and Boulder Basin is inadequate to determine if Vollenweider's relationship is even applicable to the Lake Mead System.

(iii.) As previously discussed, Vollenweider's relationship is a semi-empirical one based on data derived primarily from temperate North American and European natural lakes. It assumes complete mixing, which is probably not the case in Las Vegas Bay due to the greater density of the Las Vegas Wash inflow (Deacon 1976). A substantial fraction of the inflowing nutrients from Las Vegas Wash <u>may</u> be flowing unutilized beneath the photic zone through Las Vegas Bay and Boulder Basin. This would result in a lower <u>effective</u> loading rate than the Vollenweider equation indicates. On the other hand, since the Vollenweider equation was derived from data on temperate lakes and Lake Mead is more equivalent to a tropical lake (in regard to temperature and length of growing season), any given nutrient loading rate may result in higher productivity than implied by the Vollenweider relationship due to higher rates of nutrient turnover and biological production.

All of these factors argue against basing water quality strategy decisions for Lake Mead on a strict application of the Vollenweider relationship.

Based on our review of the existing literature and field investigation, we generally agree with previous investigators that nutrient loading of Las Vegas Wash contributes to water quality deterioration in Las Vegas Bay and that a reduction in phosphorus inflow to Las Vegas Bay would probably result in some improvement of water quality there. However, we are not convinced that AWT represents the most reasonable solution to the problem.

At the present time, sewage effluent enters the Lake in the worst possible location for producing or accelerating eutrophic conditions in Las Vegas Bay. Many researchers have noted that phytoplankton productivity and nutrient levels are higher in tributary arms than in the main body of lakes and reservoirs due to the nutrient inflow (Goldman & Wetzel 1963, Goldman and Carter 1965, Kimmel and Lind 1972, and many others). In Lake Mead, a situation ideal for the natural formation of eutrophic conditions in Las Vegas Bay (i.e., nutrient inflow via a tributary stream to a relatively shallow and semi-enclosed bay) has been severely aggravated by increased nutrient loading of the tributary (Las Vegas Wash) via domestic drainage of Las Vegas residential areas and wastewater treatment plant effluent.

Because Las Vegas Wash currently constitutes a point source of phosphorus loading for Las Vegas Bay, the reduction of P inflow would probably improve water quality conditions in the bay. However, the degree of this improvement is extremely problematic. As discussed above, Las Vegas Bay would tend to be more eutrophic than Boulder Basin even in the absence of wastewater inflow due to its morphometry and the fact that it has a tributary. Nutrient loading of Las Vegas Wash has merely aggravated this natural tendency. Therefore, although a reduction of P loading via AWT would improve the condition of Las Vegas Bay (where the problem is most severe), it is unlikely that this improvement would be as dramatic as might be generally expected, and in fact, might not be noticeable to recreational users. In addition, information on the operation and maintenance of other AWT plants, such as that at Ely, Minnesota (Kibby and Hernandez, 1976), indicates clearly that benefits from AWT must be balanced against certain unavoidable costs. These costs include a high utilization of resources (e.g., electricity, petroleum products and lime) as well as significant discharge of air pollutants (e.g., CO_2, Cl_2, SO_2, NO_x, and hydrocarbons) which are associated with the energy requirements for plant operation.

If point-source wastewater inflow to Lake Mead is to be continued, a diversion of the discharge point from Las Vegas Wash to Boulder Basin should be seriously considered. "Permissible" and "dangerous" nutrient loading rates are functions of the volume of the water body receiving the effluent. Regardless of the wastewater treatment plan eventually employed, a given nutrient loading rate would have much less visible impact if the effluent directly entered the large Boulder Basin water mass rather than first flowing through Las Vegas Bay. Additionally, it seems possible that Las Vegas Bay and Boulder Basin are actually affected by only a fraction of the Las Vegas area wastewater inflow and much of the problem now is transferred downstream. Although this possibility may minimize the direct effects of Las Vegas-derived wastewaters on Lake Mead, it forces the serious consideration of the lower

Colorado River system in eventual decisions on wastewater treatment alternatives. The Lake Mead water quality problem should not be considered an isolated one but rather as including the entire lower Colorado River system.

It appears that the most generally beneficial wastewater treatment strategy would be one in which nutrient-rich wastewater effluent was conserved and utilized in this rather infertile desert region rather than being wasted by flushing it into Lake Mead and consequently causing the degradation of water quality in both Lake Mead and the lower Colorado River. Verduin (1976) recently discussed the potential of utilizing secondary wastewater treatment effluents in creating "environmental protection parks". The following listing summarizes the potential effects of various wastewater treatment alternatives.

ALTERNATIVE	POTENTIAL EFFECTS
1. AWT with continued effluent discharge to Las Vegas Wash (LVW)	Substantial reduction of P but continued high levels of N in effluent. Las Vegas Bay (LVB) water quality will probably improve somewhat, but will likely remain highly productive. Substantial loss of nutrient-rich wastes in a nutrient-poor region. Potential atmospheric degradation. High cost.

2. AWT with effluent discharge diverted to Boulder Basin (BB)	Improvement in LVB water quality with probably little change in BB water quality. Again, substantial loss of nutrient-rich wastes in nutrient-poor region. High cost.
3. AWT with biological stripping of nitrogen and remaining P, low-level effluent release to LVW, most release to BB	- as above, but with much less nutrient waste: Nutrient-rich sludge utilizable as soil supplement, water from oxidation ponds useable for lawns and trickle irrigation of crops, low-level release to LVW marsh sustains and/or expands wildlife area, harvest of marsh vegetation useable for mulch. Low nutrient input produces least eutrophicating effects on Lake Mead and lower Colorado River. Very costly.
4. Upgraded Secondary Treatment (UST) with continued effluent discharge to LVW	- little if any reduction of P or N, continued high level nutrient loading of LVW and BB, continued nutrient accumulation in LVW sediments ultimately resulting in lower recovery rate when nutrient loading rate is finally reduced. Continued and

probably increased problems re: eutrophication of LVB, BB, and lower Colorado system. Least costly, but least acceptable alternative.

5. UST with effluent discharge to BB.	- as in 2, but since no P removal involved, effect on water quality of BB and lower Colorado likely to be more noticeable in a shorter period of time. Relatively low cost, but not particularly acceptable because of nutrient waste and high nutrient input to BB and lower Colorado.
6. UST with biological stripping of both N P, low-level release to LVW, most release to BB	- as in 3, but much less costly.

From this summary evaluation of alternatives, it appears that improved secondary treatment in combination with biological stripping in ponds and an expanded marsh in the Las Vegas Wash would be most advantageous from both economic and ecological standpoints. A diagram of such a treatment scheme is presented in Figure 13.

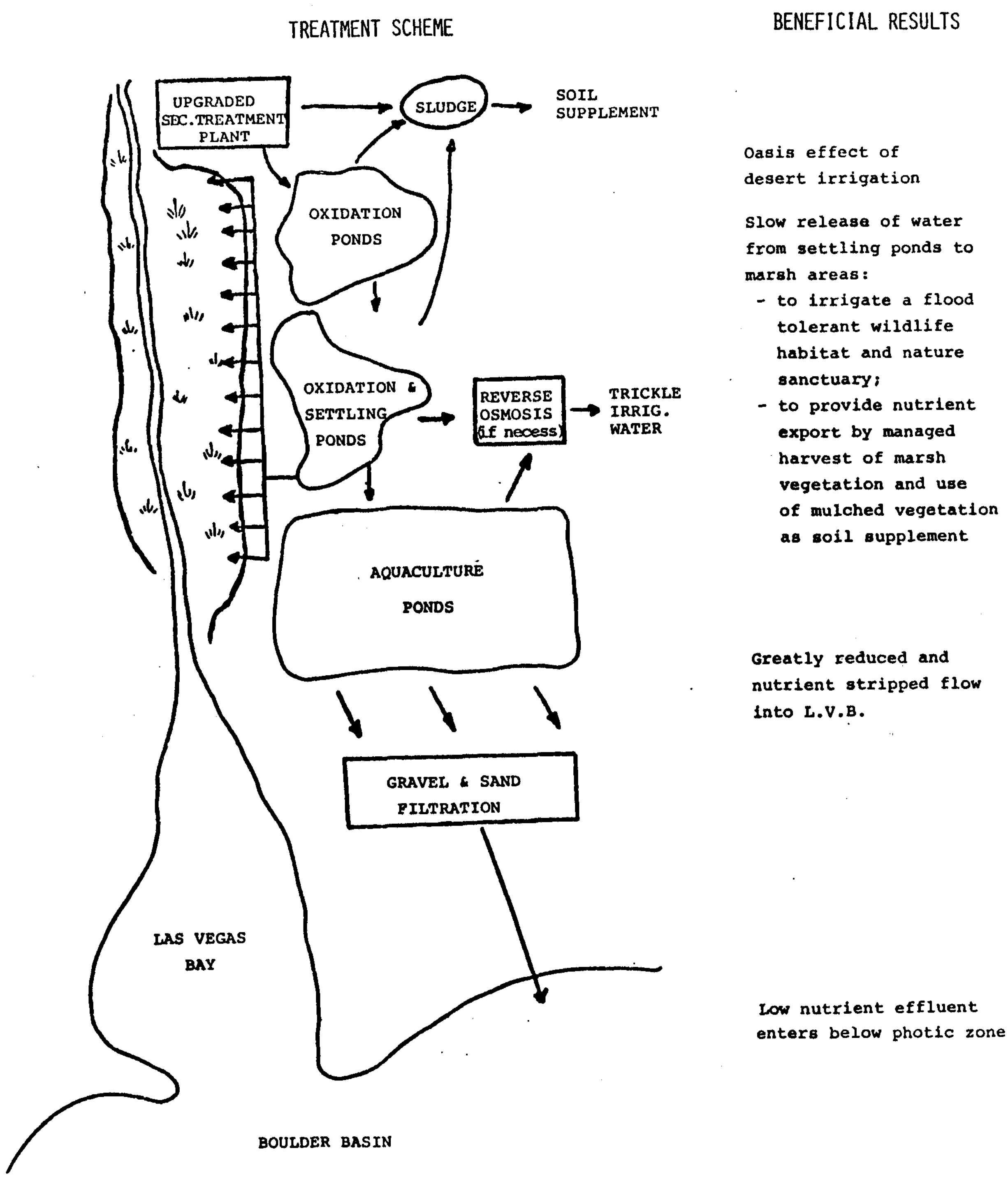

Figure 13. Proposed wastewater treatment scheme including secondary treatment, biological stripping in ponds of both N and P, use of wastewater and sludge as nutrient subsidies for agricultural purposes, and expansion of the Las Vegas Wash marsh to provide additional nutrient stripping capacity, improved waterfowl and wildlife habitat, and an "environmental park"-like recreation area. ERA study.

A proper evaluation of alternatives requires a more quantitative approach than is available from the reports summarized here. Aside from Everett's (1972) unsatisfactory model, the use of Vollenweider's criterion for estimating permissible loading rates and for justifying water quality standards has been the only attempt at integrating the large amount of data for a predictive purpose. However, this criterion is unsatisfactory both because it is based largely on temperate lakes which do not share Lake Mead's unique climatology and because it assumes a homogeneous water mass that is an inadequate model of the system under study.

At present, there is almost enough data to construct a much more realistic predictive model of algal growth in Boulder Basin, including Las Vegas Bay. With the addition of information on current flow and on the stimulatory effect of Las Vegas Wash water on algal production, it would be possible to estimate the consequences of introducing treated (by AWT or some other process) sewage effluent at one or more selected points in the Basin. Much of the information required on water flow could be deduced from Basin morphology, wind patterns, and the flow rates and densities of the point sources. The stimulatory effect of sewage effluent can be quantified on the basis of standard ^{14}C bioassay procedures.

It would be shortsighted to plunge into a major investment in AWT without any real assurance of its usefulness in this situation. Careful analysis of the data already collected and the addition of information on the interactions between effluent nutrients and Lake Mead algae would minimize the chances of bad planning. Admittedly, the time is short, but the prospects of a misspent 90 million dollars (plus substantial annual maintenance costs) must provide some balance to the decision.

VII. CONCLUSIONS

1. Although some points of methodology, investigative approach, and interpretation of results can be argued, previous investigations have been adequate for describing the general limnological characteristics of Lake Mead.

2. Our field investigation verified that within Las Vegas Bay algal productivity and nutrient concentrations decrease and water transparency increases with increasing distance from Las Vegas Wash. Conditions at Boulder Basin stations were not very different from each other.

3. We agree that excessive algal growth has been a problem in inner Las Vegas Bay, but the problem did not appear to be as severe as we had anticipated.

4. Preliminary nutrient enrichment bioassay experiments suggest that phosphorus is the primary limiting nutrient in most of Lake Mead. In inner Las Vegas Bay, the elevation of P levels by nutrient loading shifts the balance to nitrogen limitation.

5. If the reduction of a single nutrient from wastewater is eventually to be attempted, phosphorus is the obvious nutrient to remove since:

   a. it is the primary limiting nutrient most likely to be in short supply;
   b. it is technologically feasible (although very expensive) to remove via AWT; and,

c. nitrogen sources are more diffuse and, therefore, less controllable than those of phosphorus.

6. The reduction of P levels in wastewater inflow to Las Vegas Wash would improve Las Vegas Bay water quality somewhat, but probably not to the extent generally expected.

7. Due to the morphometry and the presence of a tributary, Las Vegas Bay would naturally tend to be more eutrophic than Boulder Basin even in the absence of wastewater inflow.

8. Although rather large discrepancies in algal productivity estimates cause the trophic status of Boulder Basin and Las Vegas Bay to be in question, we would classify Boulder Basin as moderately productive (ca. mesotrophic) and Las Vegas Bay as considerably more productive (ca. eutrophic). Extremely eutrophic conditions were not observed, and in comparison with highly eutrophic lakes elsewhere, may not exist.

9. Wastewater effluent currently enters the lake at the worst possible place for producing excessive algal growth problems even if much of the flow doesn't mix into Bay waters. Regardless of the treatment strategy eventually employed, enrichment effects on Lake Mead could be minimized by diverting the effluent into Boulder Basin rather than continuing to discharge into Las Vegas Bay.

10. Since it is possible that much of the Las Vegas Wash inflow may pass through Las Vegas Bay, Boulder Basin, and into the lower Colorado River, consideration of the water quality of downstream waters must be

included in deciding on the water treatment strategy to be employed.

11. We are not convinced that AWT is the most appropriate solution to Lake Mead water quality problems. Secondary wastewater treatment combined with biological stripping of both nitrogen and phosphorus in ponds and an expanded Las Vegas Wash marsh would provide a more economical and ecologically-sound alternative than AWT.

12. The data required for a reliable determination of inputs and loading rates are not existent at this time. An uncritical application of Vollenweider's relationship for the purpose of establishing water quality criteria (as was done in establishing the 0.5 mg l^{-1} P standard) and for formulating wastewater treatment strategies for Lake Mead and the lower Colorado River would be a serious mistake.

13. The major inadequacy of the investigations conducted to date has been a failure to directly address the specific problems of:

(i.) determination of surface and deep circulation patterns in Las Vegas Bay and Boulder Basin, and particularly the fate of the Las Vegas Wash inflow;

(ii.) determination of the growth response of the Lake Mead algal community to nutrient additions;

(iii.) identification of the major nutrient limiting factors for the Lake Mead algal community, and more specifically for the major bloom organisms;

(iv.) direct consideration of the relative capabilities of various wastewater treatment alternatives and the response of the Lake Mead algal community and bloom organisms to equivalent nutrient additions.

Information on these problem areas is necessary in order to determine if AWT can be expected to significantly decrease the eutrophication of Las Vegas Bay, and to identify the best location for treated sewage effluent to enter the lake in regard to producing the least objectionable consequences aesthetically and ecologically on Las Vegas Bay and Boulder Basin.

14. Previous investigations also have neglected several aspects of the problem which are important for formulation of a comprehensive water quality program:

(i.) Downstream effects of the inflow of domestic wastes to Lake Mead.

(ii.) The effect of water level fluctuations on nutrient loading levels of Las Vegas Bay and Boulder Basin.

(iii.) The magnitude of nutrient losses by sedimentation processes, the extent of nutrient return from the sediments under present conditions, and the probable magnitude of internal nutrient loading from the sediments upon the eventual reduction of external nutrient loading. These factors are particularly important in regard to the recovery rate of Las Vegas Bay after nutrient loading is reduced or eliminated.

(iv.) The effects of uncoordinated and sometimes counterproductive activities of Las Vegas and Lake Mead agencies on the overall effectiveness of a comprehensive water quality program. For example, unless done properly and with full consideration of the density structure and circulation characteristics of Boulder Basin, a back-pump storage operation at Hoover Dam could result in nutrient redistribution which would more than cancel out positive effects of nutrient removal from wastewater treatment plant effluent.

We strongly suggest that information pertaining to the problem areas listed above be obtained prior to making a major investment in water treatment technology which may not resolve the problems at hand.

VIII. RECOMMENDATIONS

1. In view of the deficiencies in existing data identified in this report, we recommend that a decision on AWT be deferred until certain essential information is obtained. The most important informational requirements are to:

(i.) Determine the actual circulation and flow patterns in Las Vegas Bay and Boulder Basin with emphasis on the fate of the Las Vegas Wash inflow.

(ii.) Establish the role of eroded soil on nutrient availability and algal production.

(iii.). Quantify the growth of Lake Mead algal communities and bloom organisms in water equivalent to that produced by various wastewater treatment alternatives.

(iv.) Better quantify nutrient fluxes to and from the sediments under present conditions in Las Vegas Bay and Boulder Basin, and determine the magnitude of internal nutrient loading from the sediments to be expected upon the eventual reduction of nutrient loading to Las Vegas Bay.

(v.) Assess the most probable downstream effects of the alternative wastewater treatment strategies under consideration for Lake Mead.

(vi.) From the above information, develop a predictive model of algal growth in Lake Mead under various wastewater treatment strategies.

2. We recommend that a committee be formed (or an existing committee be expanded) to coordinate the activities of agencies in the Las Vegas-Lake Mead area in regard to projects related to Lake Mead water quality. This committee should include representatives of the Clark County Sanitation District, the Environmental Protection Agency, the Bureau of Reclamation, the National Park Service, and independent scientific advisors expert in the areas of wastewater treatment, hydrology, and limnology. This committee should specifically strive for the development and maintenance of a comprehensive and ecologically-sound water quality program for Lake Mead and the lower Colorado River.

3. We recommend that lake level fluctuations be considered in attempts to predict the effects of nutrient inflow on water quality. More specifically, if Vollenweider's "permissible" loading relationship or other models are to be used to establish water quality criteria, calculations should be based on the lowest probable lake levels in order to avoid serious water quality deterioration during low-volume periods.

4. We urge that secondary wastewater treatment coupled with biological stripping of nutrients and water and nutrient reclamation be seriously considered as an economical and ecologically-viable alternative to AWT.

5. Additionally, further consideration should be given to relocating the point of effluent discharge from Las Vegas Wash to Boulder Basin (as described in Alternative 6, Section VI of this report).

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